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DETERMINATION OF ILS CATEGORY II DECISION HEIGHT WINDOW REQUIREMENTS

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16. Abstract

The current definition of a successful ILS Category II approach is given in FAA Advisory Circular No. 120-20 in terms of maximum allowable airplane dispersions at the 100 ft decision height. These maximum dispersions are the same for all air carrier aircraft. It is conceivable that the given decision height dispersion limits are inappropriate for some airplane/control-system combinations. This report describes a method for determining the appropriate longitudinal and lateral decision height dispersion limits for any airplane/control-system combination. An example is worked out to clarify the steps required.

The results show that the current longitudinal decision height dispersion limits are well suited for a DC-8 with the example control system, but that the lateral limits are too loose to guarantee acceptable touchdowns with the example system subjected to the wind and shear disturbances recommended by the FAA in AC 120-20.

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FOREWORD

The research reported here was performed under Contract NAS2-4892 between Systems Technology, Inc., Hawthorne, California, and the National Aeronautics and Space Administration. The NASA Project Monitor was Thomas E. Wempe. The STI Technical Director was Duane T. McRuer, and the Project Engineer was Walter A. Johnson.

ABSTRACT

The current definition of a successful ILS Category II approach is given in FAA Advisory Circular No. 120-20 in terms of maximum allowable airplane dispersions at the 100 ft decision height. These maximum dispersions are the same for all air carrier aircraft. It is conceivable that the given decision height dispersion limits are inappropriate for some airplane/control-system combinations. This report describes a method for determining the appropriate longitudinal and lateral decision height dispersion limits for any airplane/control-system combination. An example is worked out to clarify the steps required.

The basic technique used is to define the limits of acceptable touchdown conditions for the airplane of interest, and then to determine the decision height conditions that correspond to the touchdown limits. The only disturbance inputs considered are steady winds and wind shears.

The results show that the current longitudinal decision height dispersion limits are well suited for a DC-8 with the example control system, but that the lateral limits are too loose to guarantee acceptable touchdowns with the example system subjected to the wind and shear disturbances recommended by the FAA in AC 120-20.

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SECTION I

INTRODUCTION

The current FAA definition of a successful ILS Category II approach is given in Ref. 1 in terms of maximum acceptable airplane dispersions at an altitude of 100 ft above the runway. In essence, the FAA has defined a "window" that an airplane must be within at the 100 ft decision height. However, this window is the same for all air carrier airplanes and control systems. Presumably the FAA had in mind a typical jet transport when it devised the window. However, it is easy to imagine an airplane plus controller for which the given window is too restrictive, as well as an airplane plus controller for which it is too conservative. The idea that a single window may not be appropriate for all airplanes and control systems was the motivation behind the study that this report summarizes. The primary purpose of the study was to determine how logically to set the decision height window boundaries for any given airplane plus control system.

In this report a technique is presented that will lead to a logical determination of the variables pertinent to a decision height window, as well as a set of acceptable limits for these variables. Briefly, the technique and consequences of its application can be summarized as follows.

- An airplane and control system (for which a Category II window is desired) are selected.
- A "successful" touchdown is defined for the selected airplane in terms of the maximum acceptable dispersions of all pertinent variables at touchdown.
- The disturbance environment is defined from the decision height to the ground.
- The pertinent decision height variables are determined, as well as their limiting values that still result in an acceptable touchdown in the presence of the disturbance environment.

- These pertinent variables constitute the decision height window dimensions, while the limiting values give the maximum size of the window.

- If the window is trimmed to make it "rectangular," then a tradeoff can be made among the pertinent window limits to minimize the number of missed approaches. (This is based on the computed dispersions of the pertinent variables at the decision height.)

- An overall system improvement can be achieved by defining state variables at the decision height such that when values of all the state variables are less than some precomputed values, then a successful touchdown will result, and a value greater than the computed value for any (or all) of the state variables will lead to an unsafe touchdown. (These state variables may include known wind and/or other environmental conditions.)

- The state variable definitions could be mechanized electronically to give an approach monitor which indicates when to execute a missed approach and when to continue the approach to touchdown. Such a device would serve the dual function of providing an approach monitor as well as a missed approach decision computer.

The technique is presented and described by carrying out example calculations for a DC-8 airplane with an automatic flare and decrab control system.* The limits of acceptable touchdown conditions were obtained from Ref. 2 and an informal industry consensus (e.g., Refs. 3, 4, 5, and 6). The disturbance inputs from the decision height (100 ft) down to the ground were also taken from Ref. 2. These include steady head-, tail-, and crosswinds, as well as wind shears. Random gusts from the decision height down to the ground were not directly considered for two reasons. First, the currently available analytical gust models are not appropriate near the ground. And, second, the high frequency part of the random gusts from 100 ft down to the ground are not of interest anyway, because they do not

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*Although the technique is equally applicable to a manually controlled airplane, it is simpler to present an example involving only automatic components.

significantly affect the path of the airplane; only the lower frequency gusts are significant. But, for the time intervals of interest, the lower frequency gusts can be represented as steady winds and wind shears. The net result is that we can replace the random gust disturbances below 100 ft with equivalent steady wind and shear inputs. The question of wind shear magnitude then arises. The magnitude of wind shear used in this study is that specified in Ref. 2; namely, 8 kt/100 ft from 100 ft down to the ground. By selecting this moderate shear input we have ignored the occasional much larger shears that can occur during the last few seconds prior to touchdown. Reference 7 points out that these larger shears often have significant consequences. For example, Ref. 7 shows a strong correlation between hard landings and moderate wind gusts (that give large effective wind shears) just prior to touchdown. But, in spite of having neglected this significant disturbance input, the inclusion of such shears in our simulation would not change the resulting Category II windows that were obtained, because there would still be no correlation between decision height conditions and hard landings. Only if we were trying to estimate touchdown distributions or accident rates would these large effective shears be required.

The determination of the decision height conditions that give the limiting touchdown conditions was accomplished with the aid of a six-degree-of-freedom analog computer simulation of the final part of the approach. It was originally anticipated that a completely analytical technique would be used. But due to nonlinearities in both the longitudinal and lateral situations this was not feasible. It was necessary to compute forward from the initial state (at the decision height) down to touchdown, where the state of the system was recorded. The computational procedure consisted of generating parametric plots of the touchdown variables versus the initial state variables for the several wind conditions. A window was then constructed from predictions of the touchdown state based on expressions generated from curve fits of the empirical data.

As would be expected, the simulation showed that variables with mid- to high frequency characteristics have little or no correlation between the decision height and touchdown, and therefore need not be considered in the definition of an approach window. By perturbing each of the initial state variables at the decision height and noting the effect on touchdown, it was determined that for any given wind condition the touchdown location is adequately defined as follows:

$$x_{TD} = x(d_{100}, u_{100}, \tilde{\dot{h}}_{100})$$

$$y_{TD} = y(y_{100}, \dot{y}_{100})$$

where d_{100} is glide slope deviation, u_{100} is speed deviation from trim, y_{100} is lateral deviation, and $\tilde{\dot{h}}_{100}$ is a filtered value of instantaneous sink rate. (The filter is necessary to remove the component of sink rate due to high frequency vertical gusts. These high frequency $\dot{h}$ excursions at the decision height have negligible effect on touchdown dispersions.)

Measures of the airplane dispersions at the decision height were obtained using the low level approach model described in Ref. 8.

The above paragraphs describe briefly what was done, why it was done, and how it was accomplished. The remainder of this report will describe these items in somewhat more detail and will support the following conclusion: The current FAA ILS Category II decision height window appears to be inadequate for the example airplane plus control system, and therefore it is recommended that immediate action be taken to improve the current decision height situation. In particular, the following should be considered:

- The Category II decision height window should be modified to fit the performance capabilities of the airplane-plus-control-system using it.
- A continuously updated prediction of the touchdown point (based on current situation and a system model) should be displayed for monitoring purposes.
- A missed-approach computer (based on predicted touchdown conditions) should be provided to give a go/no-go decision at the decision height.

Section II contains a description of the example system used in the calculations. Section III then follows with the determination of acceptable airplane dispersions at the decision height. Section IV contains some pertinent results from a study of Category II approach success probabilities which can be used to optimize the window tradeoffs at the decision height. And finally, Section V contains a brief summary and conclusions. The definition of a successful touchdown has been included in an appendix.

SECTION II

DESCRIPTION OF EXAMPLE SYSTEM

The overall system chosen for example calculations consists of a DC-8 aircraft with a fully automatic landing system designed to perform the following functions:

- Localizer tracking
- Glide slope tracking
- Sink rate hold (between 100 ft and flare initiation)
- Automatic flare
- Automatic decrab

The example system is summarized in the following paragraphs.

A. LONGITUDINAL SYSTEM

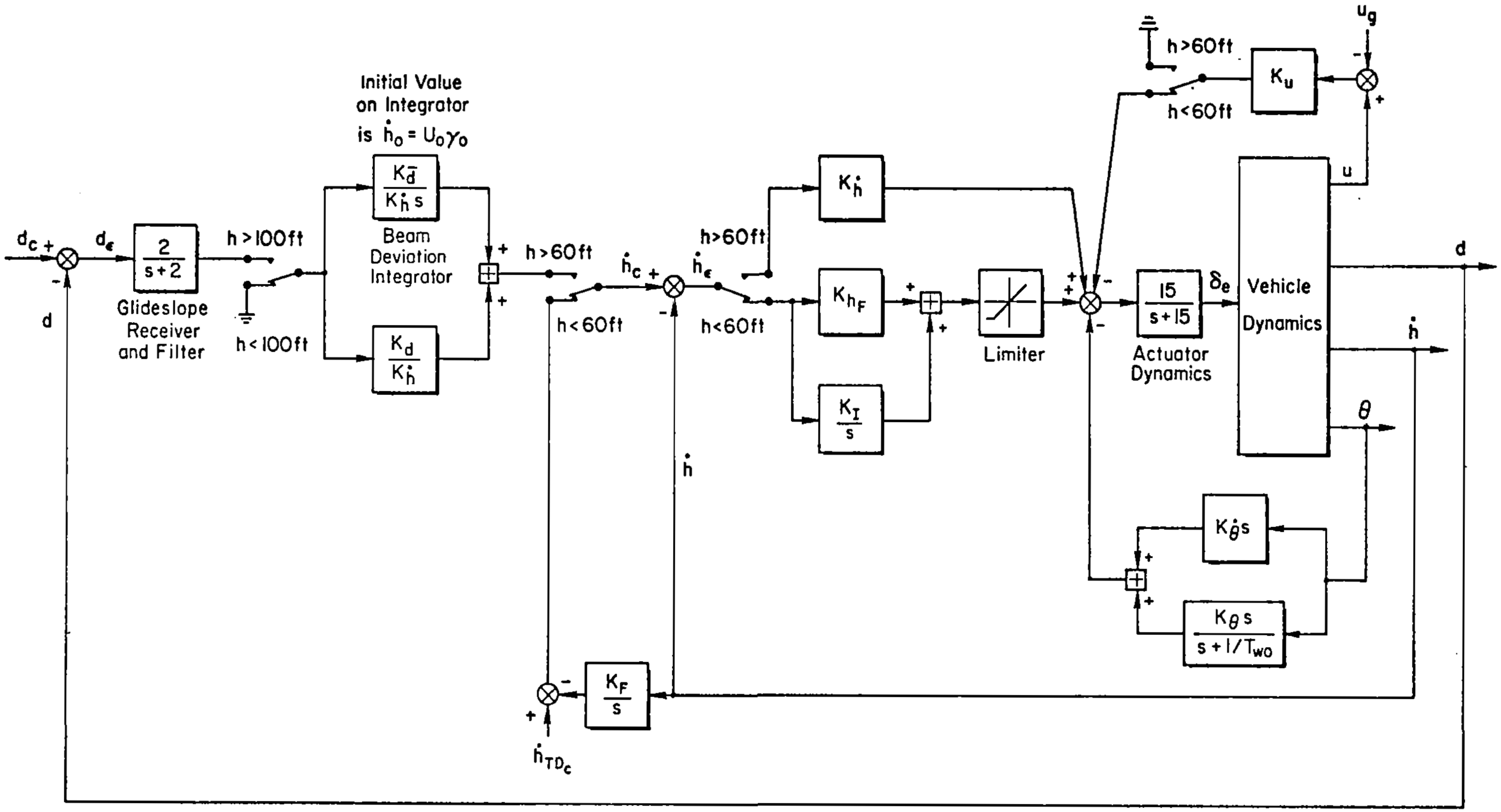
1. Glide Slope Tracking

The functions to be performed and the feedbacks used to satisfy the functional requirements during glide slope tracking are summarized in Table 1. The associated block diagram is given in Fig. 1.

TABLE 1

SUMMARY OF LONGITUDINAL FEEDBACKS USED DURING GLIDE SLOPE TRACKING

SYSTEM REQUIREMENTS	FEEDBACKS
Short-period attitude stiffness	Pitch attitude, θ, with washout to provide mid-frequency windproofing
Short-period damping	Pitch attitude rate, $\dot{\theta}$
Path acquisition and stiffness	Beam deviation, d
Path damping	Altitude rate, $\dot{h}$
Low frequency windproofing and path angle trimming	Beam deviation integration, $\int d\, dt$



$K_{\bar{d}} = -.000768 \frac{\text{rad}}{\text{ft/sec}}$

$K_d = -.00867 \frac{\text{rad}}{\text{ft}}$

$K_{\dot{h}} = -.0256 \frac{\text{rad}}{\text{ft/sec}}$

$K_{\dot{\theta}} = -2.0 \text{ sec}$

$K_\theta = -2.0$

$\frac{1}{T_{wo}} = .7 \text{ sec}^{-1}$

$K_F = .152 \text{ sec}^{-1}$

$\dot{h}_{TD_c} = -2.0 \frac{\text{ft}}{\text{sec}}$

$K_{h_f} = -.014 \frac{\text{rad}}{\text{ft/sec}}$

$K_I = -.00307 \frac{\text{rad}}{\text{ft}}$

$K_u = -.00069 \frac{\text{rad}}{\text{ft/sec}}$

Figure 1. Summary Block Diagram of Longitudinal System

2. Glide Slope Extension

At 100 ft above runway elevation the glide slope extension phase is initiated. In this phase the glide slope signal is removed and a constant sink rate is commanded. The value of this sink rate is the output of the beam deviation integrator (see Fig. 1) at 100 ft, and as such represents the average sink rate over the last minute or so of flight prior to reaching 100 ft. The logic used in switching modes is illustrated in the system block diagram shown in Fig. 1.

3. Flare Mode

A constant sink rate is commanded from 100 ft down to the flare initiation height (60 ft), where the flare equation (Eq. 1) is switched into the loop (as illustrated in Fig. 1). The flare is accomplished by using a sink rate command proportional to altitude. Thus the ideal (or commanded) flare path is an exponential function of time. The required control equation is:

$$\dot{h}_c = -K_F h - \dot{h}_{TD_c} \tag{1}$$

Because the flare is initiated at 60 ft and the desired sink rate at touchdown is 2 ft/sec, the constants in Eq. 1 are

$$K_F = 0.152 \text{ sec}^{-1} \quad \text{and} \quad \dot{h}_{TD_c} = -2 \text{ ft/sec}$$

The parallel integrator (K_I/s) shown in the flare system forward loop (Fig. 1) is used to improve the pitch attitude response to the flare commands. If a sink rate error is not removed immediately, then the integrator causes more elevator to be used. This is particularly important at the start of flare where the airplane cannot pitch up rapidly enough to follow the desired path (because it requires a step change in pitch attitude to go from a straight path to an exponential path). An alternative technique that could be used to alleviate this problem is to inject an open-loop ramp or step attitude command in the forward loop. However, for our purposes, the system with the parallel integrator was felt to be sufficient; and it has the additional capability to regulate against external disturbances (giving closed-loop control).

A low gain airspeed-to-pitch-attitude feedback was included to insure a safe flare in the event of a rapid airspeed bleedoff near touchdown, such as might occur in the presence of a large wind shear.

The throttles are retarded linearly from approach thrust to flight idle (a 19 percent thrust decrease) starting at 50 ft above the runway. A throttle retard rate of 4 percent/sec was used. The engine characteristics were modeled as follows:

$$\frac{T}{T_{command}} = \frac{1}{(s + 1)(\frac{s}{1.5} + 1)} \tag{2}$$

A system survey of the flare system is given in Fig. 2 where it is seen that a forward loop gain (K_{h_F}) of −0.014 rad/ft/sec gives close to the maximum available phase margin. An additional consideration in picking this gain was that the system error signal ($\dot{h}_c$) should nominally be zero at touchdown. (Note that this implies that $\dot{h}_{TD}$ = −2 ft/sec.) By varying K_{h_F} and K_I one is able to "tune the system" so that the −2 ft/sec objective may be accomplished. A time history of the motion from 100 ft to touchdown is given in Fig. 3 for a no-wind situation, and also for an 8 kt/100 ft tailwind shear situation. Note that the system achieves a touchdown sink rate quite close to the nominal −2 ft/sec, even in the presence of wind shear.

B. LATERAL SYSTEM

1. Localizer Tracking

A summary of the localizer tracking system requirements and the corresponding feedbacks used to satisfy these requirements is given in Table 2, below. A block diagram of the complete lateral system is given in Fig. 4. It is pointed out that the bank angle command limiter (used to keep the bank angle less than 5 deg near touchdown) is only engaged when the altitude goes below 100 ft. However, the switch for this limiter was omitted from the diagram to make a little less clutter.

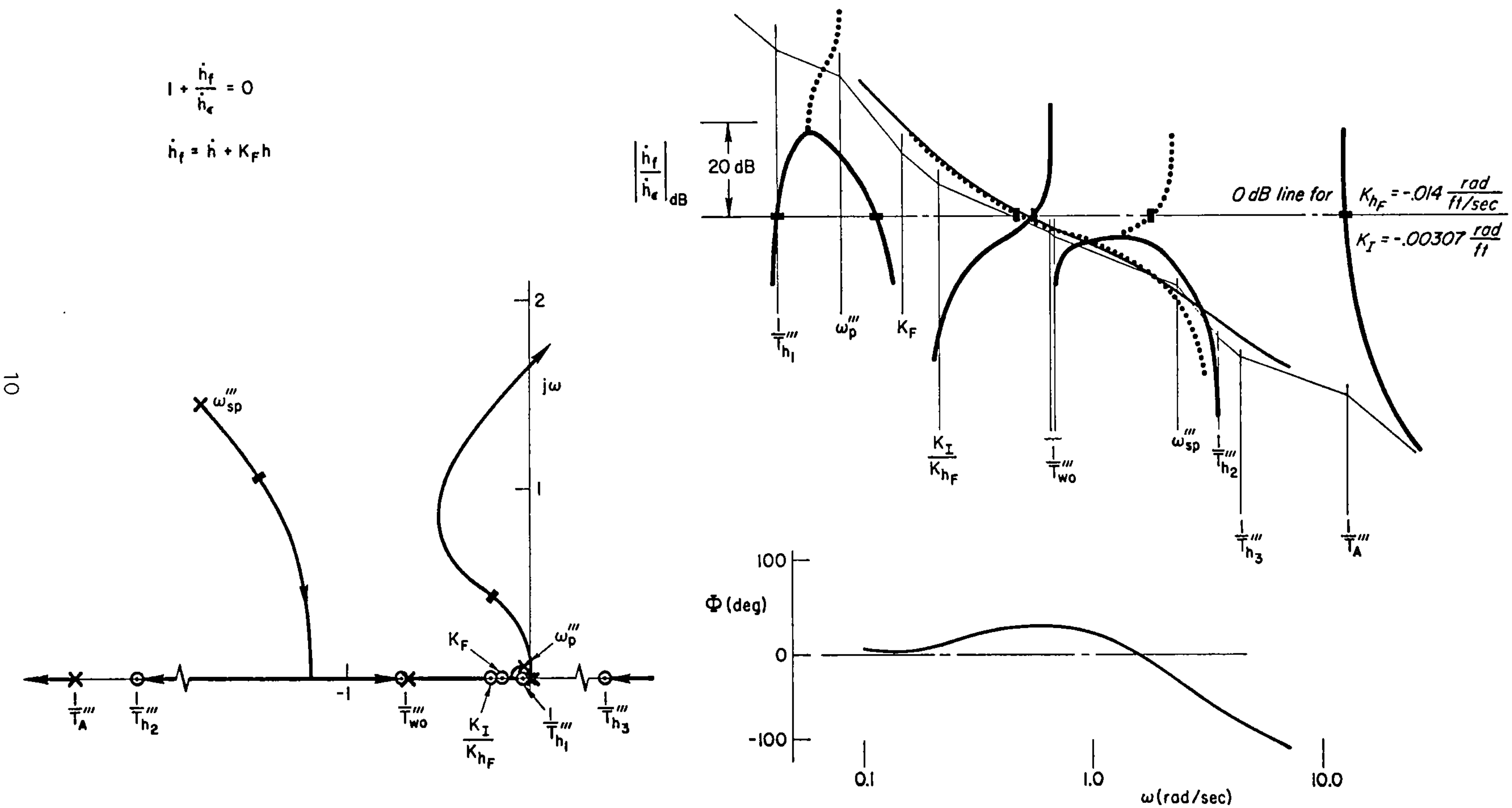


Figure 2. System Survey of Flare System

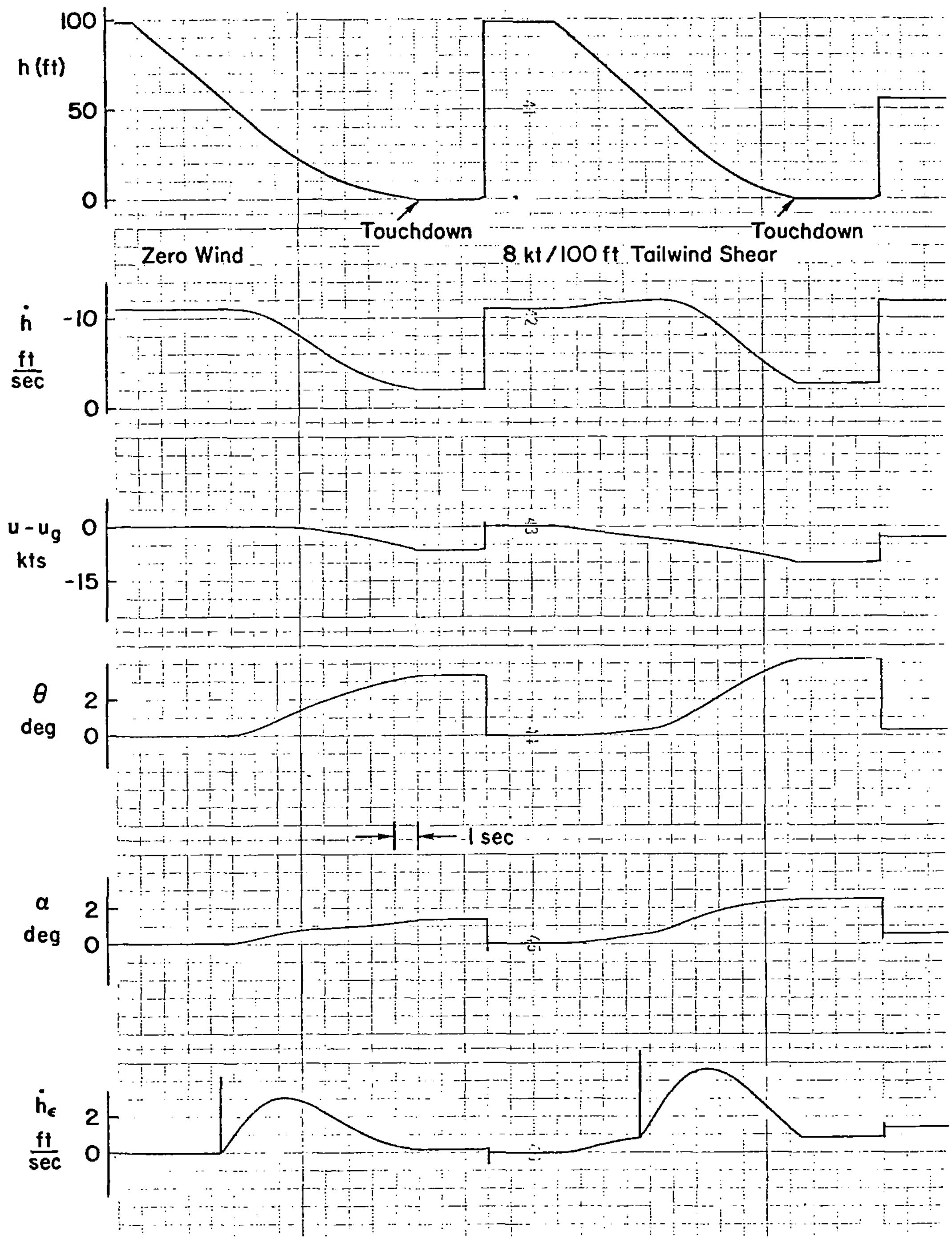


Figure 3. Flare Time Histories

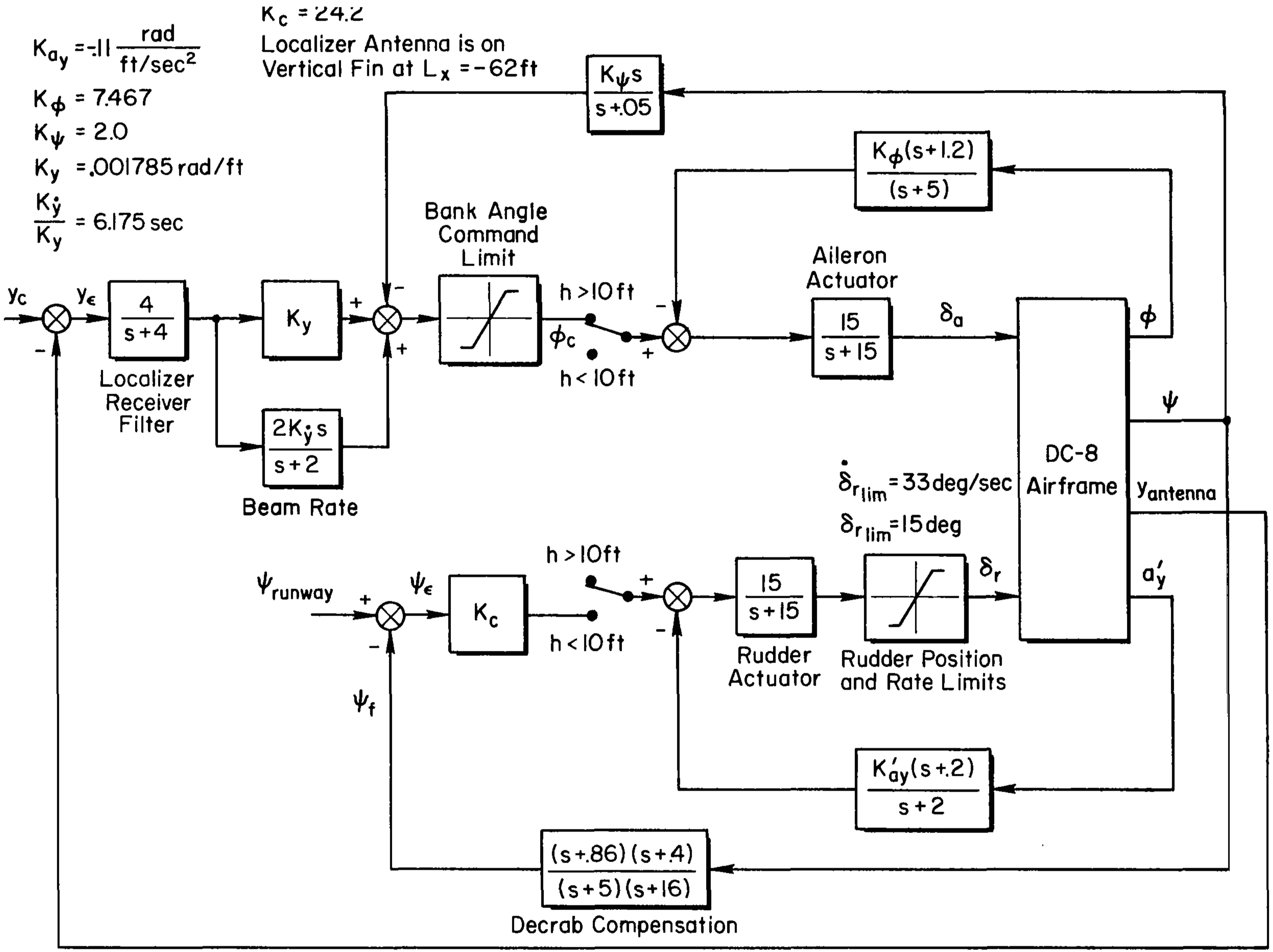


Figure 4. Lateral Control System

TABLE 2

SUMMARY OF LATERAL FEEDBACKS USED DURING LOCALIZER TRACKING

SYSTEM REQUIREMENTS	FEEDBACKS
Dutch roll damping and stiffening	Lateral acceleration a_y' with lead-lag network
Bank angle regulation	Bank angle, φ, with lead-lag network
Path acquisition and stiffness	Beam deviation, y
Path damping	Beam rate, $\dot{y}$, and washed out heading, ψ (washout is for low frequency windproofing)

The localizer tracking system was designed to have undershoot characteristics in the mid-frequency region. This was done for two reasons: (1) to reduce the tendency for large overshoots in the presence of a crosswind, and (2) to be in keeping with normal piloting technique, which is to "blend" with the beam. A time history showing the response of the system to a 100 ft lateral offset is given in Fig. 5. It is noted that the system is *nonlinear* because the φ command signal (φ_c) is saturated during the early portion of the response. A system survey of the localizer tracking system above 100 ft (when it is a linear system) is given in Fig. 6.

2. Decrab Maneuver

The decrab system is essentially a heading-to-rudder feedback loop which is closed at the decrab altitude (10 ft). The localizer signal is removed from the system, but the bank angle feedback is left in to keep the wings level during the maneuver. The decrab system block diagram was shown as part of the complete lateral system block diagram in Fig. 4. A lag-lead, lead-lag network was required to obtain the desired performance from the system, as summarized below.

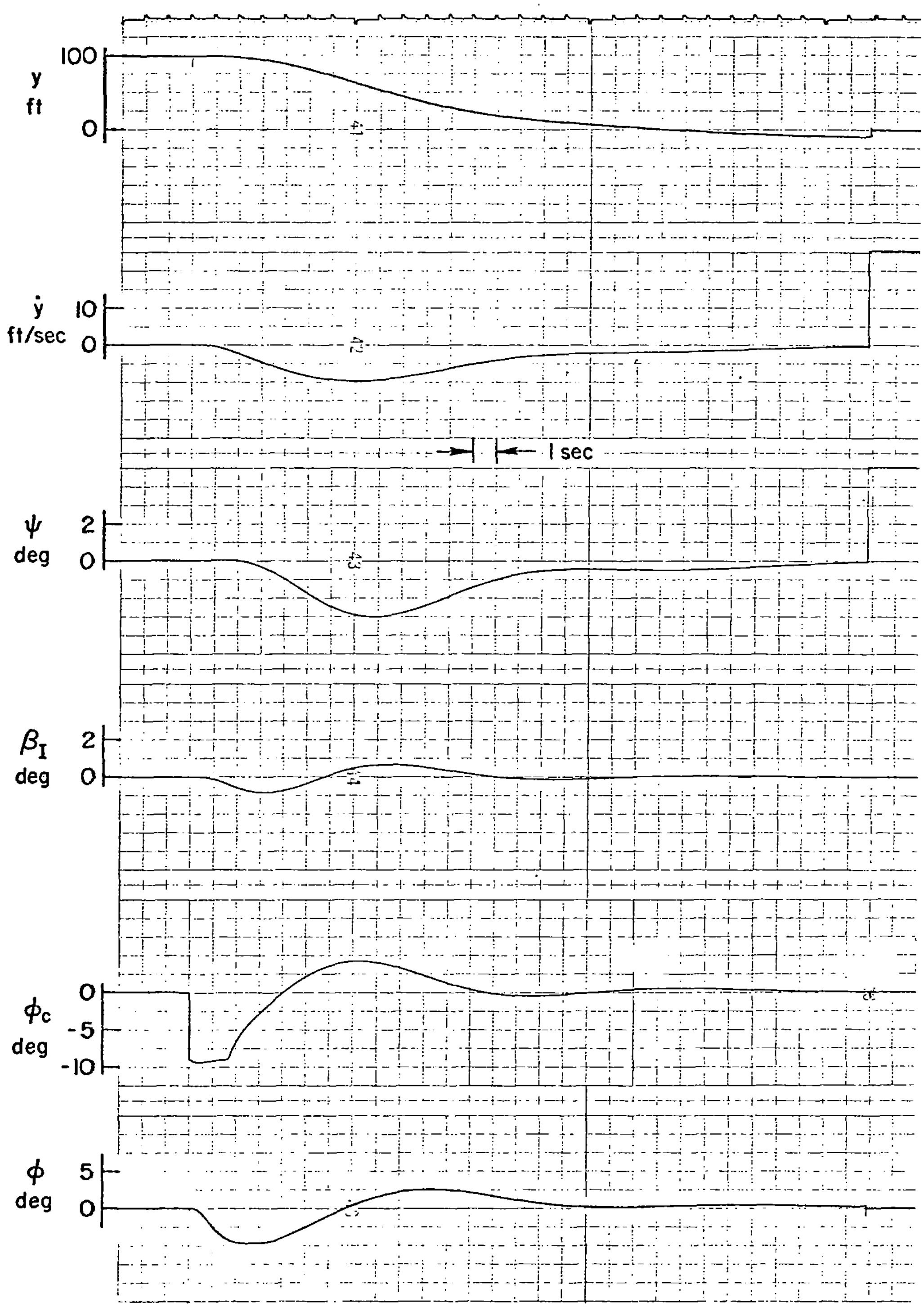


Figure 5. Response of Localizer Tracking System to Initial Lateral Offset

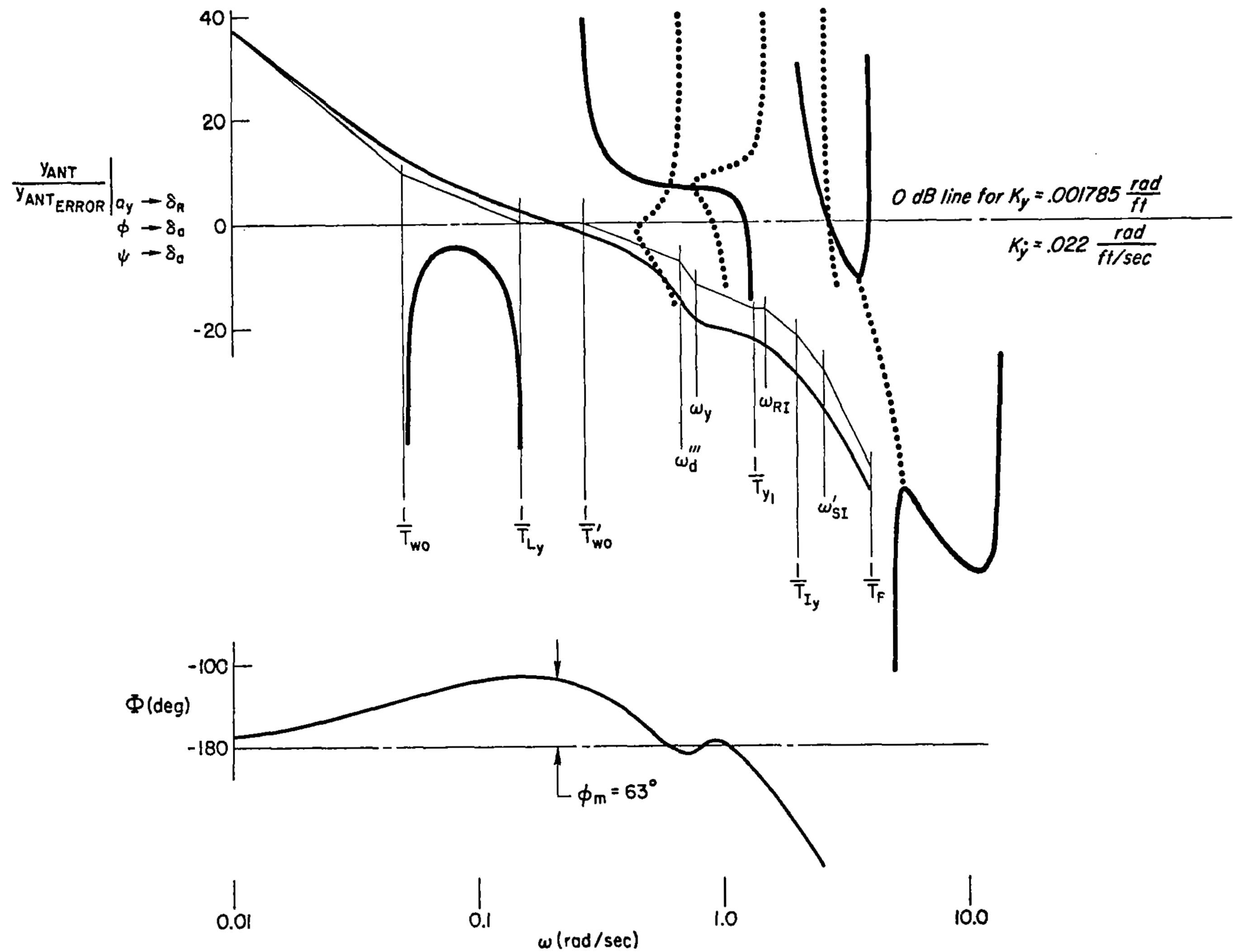


Figure 6. System Survey of Localizer Tracking System

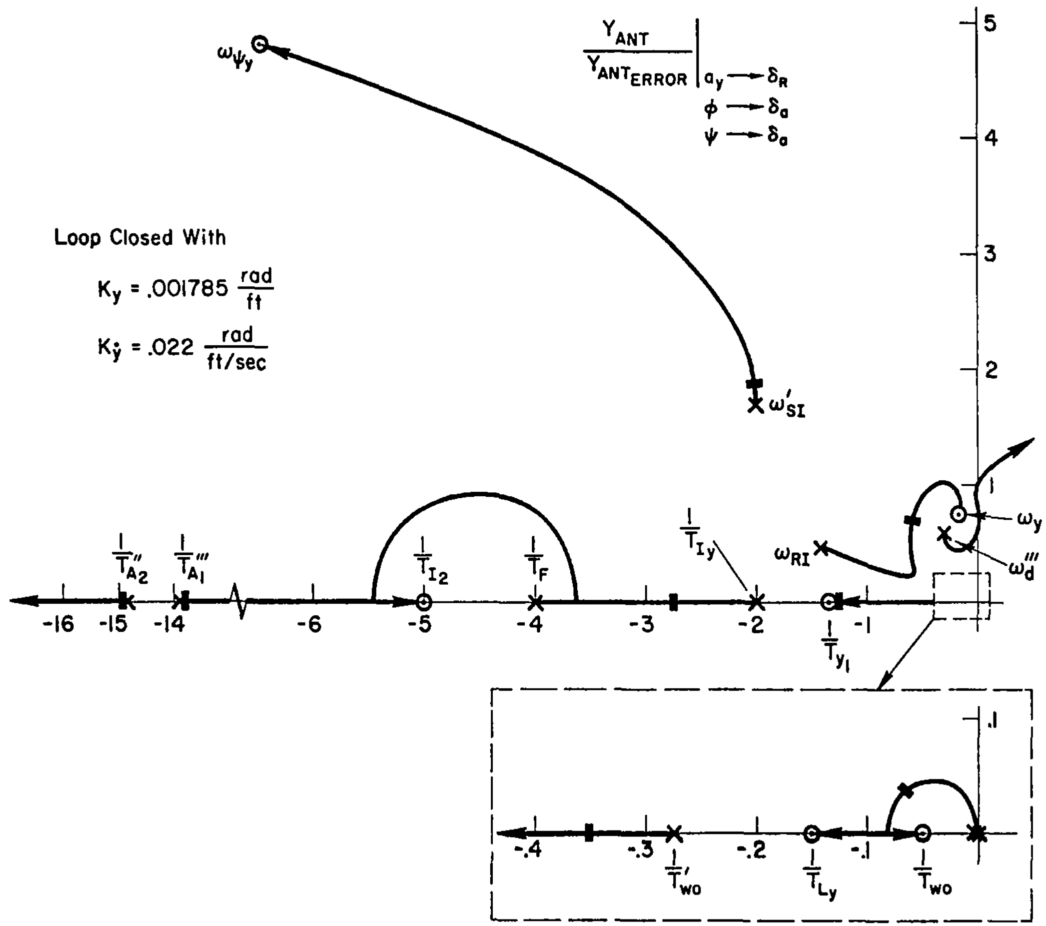


Figure 6 (Concluded)

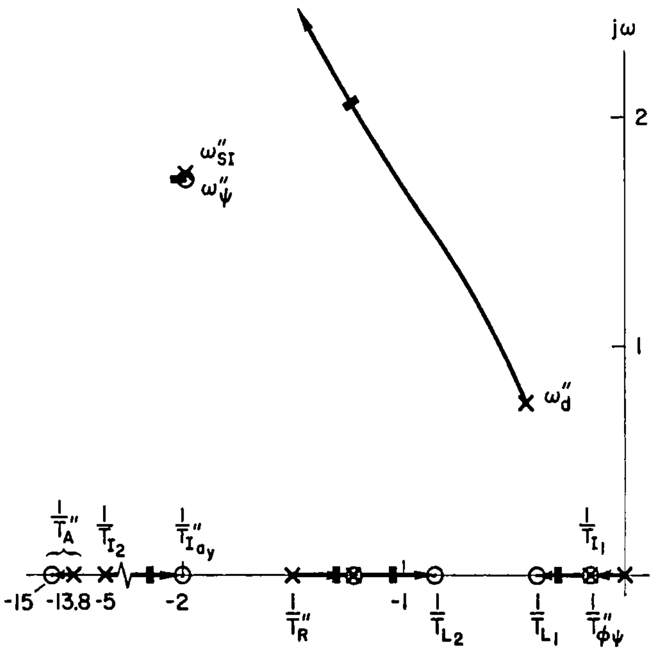
PROBLEM	SOLUTION	COMPENSATION
System overshoots due to low damping	Lead-lag network with lead at $\omega_d''{}^*$	$\frac{s + 0.86}{s + 5}$
Poor mid- to low frequency response — standoff in time response (due to long flat region on Bode plot)	Lag-lead with lag at $1/T_{\varphi_\psi}''{}^*$ and lead at 0.4	$\frac{(s + 0.4)}{(s + 0.16)}$

*Double prime indicates two inner loops have been closed ($a_y' \rightarrow \delta_r$, $\varphi \rightarrow \delta_a$).

A survey of the decrab system is shown in Fig. 7. Note that for all practical purposes the poles have been driven close to the zeros, with the exception of the dutch roll roots which make up the dominant mode of the system. The resultant closed-loop dynamics have the characteristics of a well-damped second-order system ($\zeta = 0.51$) with a natural frequency of 2.4 rad/sec. The system response during decrab for an approach with a 15 kt crosswind is illustrated in Fig. 8. Note that the heading response (ψ) has the good characteristics discussed above, even though the rudder is saturated in rate (33 deg/sec) and position (15 deg) during the early part of the response. The initial reversal in side velocity ($\dot{y}$) is due to the rudder sideforce characteristics (Y_{δ_r}). This effect delays the initiation of lateral drift by 2 sec and therefore tends to reduce the lateral dispersions at touchdown. The nominal decrab time is 3 sec. (It should be noted that the decrab altitude was increased to 20 ft in Fig. 8 only for the purpose of illustrating the transient response of the decrab system.)

Feedback Compensation

$$Y_f = \frac{(s+1/T_{L_1})(s+1/T_{L_2})}{(s+1/T_{I_1})(s+1/T_{I_2})} = \frac{(.4)(.86)}{(.16)(5.0)}$$



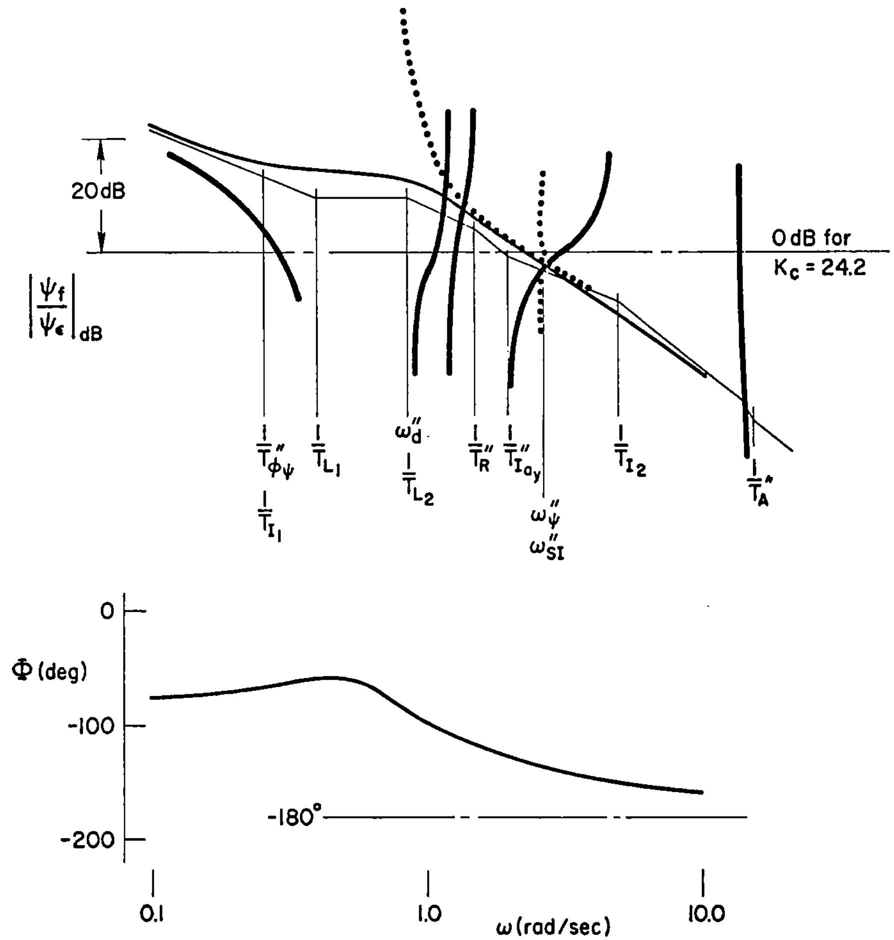


Figure 7. Decrab System

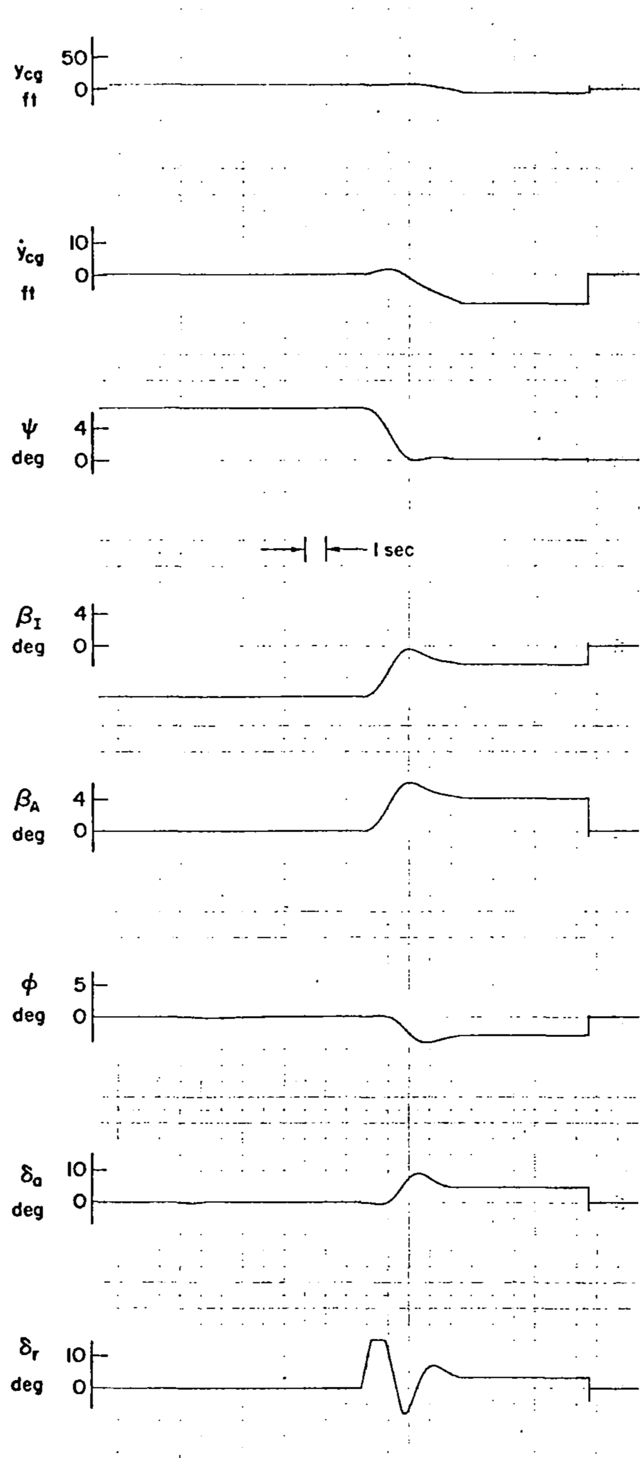


Figure 8. Decrab at 20 Ft in Presence of a Steady 15 Kt Crosswind

SECTION III

DETERMINATION OF ACCEPTABLE DISPERSIONS AT THE DECISION HEIGHT

A six-degree-of-freedom analog computer simulation was used to determine the decision height dispersions that result in the limiting acceptable touchdown conditions. The first step in this analysis was to determine the gross sensitivity of touchdown conditions to variations in each of the airplane variables at the decision height. The results of this gross sensitivity investigation showed that only a few variables at the decision height have a significant effect on touchdown conditions. These are: d_{100}, u_{100}, $\tilde{\dot{h}}_{100}$, y_{100}, and $\dot{y}_{100}$, where the subscript 100 refers to the decision height, and

- d is deviation from the glide slope beam
- u is the perturbation from trim airspeed
- y is lateral deviation from the localizer beam
- $\dot{y}$ is lateral deviation rate
- $\dot{h}$ is a filtered value of instantaneous sink rate (the filter is necessary to remove the high frequency component of sink rate caused by high frequency gusts; these high frequency sink rate perturbations at the decision height have negligible effect on touchdown dispersions, but may significantly affect the instantaneous sink rate).

As might be expected, it was found that variables with predominantly mid- to high frequency characteristics have little or no correlation between the decision height and touchdown*, and therefore need not be considered in the definition of an approach window. This greatly simplifies the search for the significant decision height variables.

It was also found that for all reasonable values of initial conditions at the decision height, and wind and shear inputs from the decision height down to the ground, only a few touchdown variables came near their respective limiting acceptable values (see appendix for the limiting acceptable values of all touchdown variables). These variables are: X_{TD}, y_{TD}, and $\dot{y}_{TD}$. All the rest of the variables were well within their respective ranges of acceptable values.

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*Data supporting this result has not been included in this report.

Having eliminated the insignificant variables early in the investigation, it still remained to determine the quantitative relations between the decision height conditions and touchdown conditions for the variables that were found to be important. The remainder of this section is devoted to this area of the investigation. It is divided into longitudinal and lateral subsections for ease of presentation.

A. LONGITUDINAL CONSIDERATIONS

For the longitudinal situation it was found that the sink rate at touchdown (for our example system) was insensitive to initial conditions at 100 ft altitude. In fact, the only longitudinal touchdown parameter that has an appreciable sensitivity to conditions at 100 ft is X_{TD} (distance down the runway measured from the threshold). Conveniently, the effects on X_{TD} due to various initial conditions at 100 ft, and wind inputs from 100 ft to the ground, turned out to be independent of one another, and essentially linear (with the exception of wind shear), over a reasonably large range of values for each variable. The resulting expression for X_{TD} is

$$X_{TD} \doteq 1620 \text{ ft} + 23\,\hat{u}_w \frac{\text{ft}}{\text{kt}} + 38\,\frac{\partial u_w}{\partial h}\,\frac{\text{ft}}{\text{kt}/100\text{ ft}} - 1.2\left(\frac{\partial u_w}{\partial h}\right)^2 \frac{\text{ft}}{(\text{kt}/100\text{ ft})^2}$$

$$+ 43\,u_{100}\frac{\text{ft}}{\text{kt}} + 20\,d_{100} + 21\,\tilde{\dot{h}}_{100}\frac{\text{ft}}{\text{ft/sec}} \qquad (3)$$

where $\hat{u}_w$ is equal to the steady wind for tail winds, and is equal to one-half of the steady wind for headwinds up to 40 kt* (tailwinds are +)

$\partial u_w/\partial h$ is the longitudinal wind shear (increasing headwind as you descend is + and is called a headwind shear)

u_{100} is the error in airspeed (from trim) at 100 ft altitude (increased speed is +)

*To be consistent with airline policy, an increased airspeed was used in the headwind case. The strategy used is that of United Air Lines, which calls for the approach airspeed to be increased by an amount equal to the gust velocity plus one-half of the steady headwind component, with the total not to exceed 20 kt (Ref. 9).

d_{100} is the deviation from the glide slope beam at 100 ft altitude (above the beam is +)

$\tilde{\dot{h}}_{100}$ is the low frequency error in trimmed vertical speed (from nominal) at 100 ft altitude (decreased sink rate is +)

A simple example shows the importance of each of the flight errors at 100 ft (and also the wind inputs) on the longitudinal touchdown position. For this example, the following conditions are assumed:

$$\text{Decreasing headwind as airplane descends}\left\{\begin{array}{l} u_W = -15 \text{ kt} \quad (\hat{u}_W = -7.5 \text{ kt}) \\[2ex] \dfrac{\partial u_W}{\partial h} = -4 \dfrac{\text{kt}}{100 \text{ ft}} \end{array}\right.$$

$$\text{Slightly slow and "climbing" back from being low}\left\{\begin{array}{l} u_{100} = -4 \text{ kt} \\[2ex] \tilde{\dot{h}}_{100} = 2 \dfrac{\text{ft}}{\text{sec}} = 120 \dfrac{\text{ft}}{\text{min}} \\[2ex] d_{100} = -9 \text{ ft} \end{array}\right.$$

These conditions can be considered somewhat "typical," in that none of the errors (or wind) is very large. When substituted into Eq. 3 these values give

$$X_{TD} \doteq \underbrace{1620}_{\text{Nominal}} + \underbrace{\underbrace{23(-7.5)}_{-173}}_{\text{Steady Wind}} + \underbrace{\underbrace{38(-4) - 1.2(-4)^2}_{-171}}_{\text{Wind Shear}} + \underbrace{\underbrace{43(-4)}_{-172}}_{\text{Speed Error}} + \underbrace{\underbrace{20(-9)}_{-180}}_{\text{Deviation from G/S Beam}} + \underbrace{\underbrace{21(2)}_{+42}}_{\text{Sink Rate Error}} \qquad (4)$$

The terms are labeled to indicate the source of each contribution. Adding up the various terms gives

$$X_{TD} \doteq 1620 - 654$$

or

$$X_{TD} \doteq 966 \text{ ft} \qquad (5)$$

For this example it is seen that each of the sources contributes about 175 ft of touchdown-point displacement, except for the sink rate error, which has a much smaller effect on the touchdown location. It is also apparent from Eq. 4 that reasonably large wind shears can cause extremely large variations in the touchdown location. In fact, a wind shear of −15 kt/100 ft (along with the same other numbers from the above example) would lead to a touchdown location only about 297 ft from the threshold. The perturbation in X_{TD} due to such a shear (alone) would be about 840 ft. This is considerably larger than the individual effects due to any "reasonable" values of the other parameters in Eq. 4.

Having determined the relation between decision height conditions (and winds) and touchdown location, it still remains to determine the limiting conditions at the decision height so that a decision height window can be specified. This is done as follows.

The maximum allowable dispersion in touchdown position (X_{TD}) is given in Ref. 2 as 1500 ft total about a nominal point on a 2σ basis with an absolute lower limit of 300 ft and an absolute upper limit of 2550 ft for a DC-8 (based on the ability of the pilot to see the required four bars of the 3000 ft touchdown zone lights at touchdown). (See the appendix for the precise requirement.) The following limits were used in this study because they place the nominal touchdown point (for the example airplane) approximately in the center of the allowable 1500 ft region.

$$800 \text{ ft} \leq X_{TD} \leq 2300 \text{ ft} \tag{6}$$

Substituting Eq. 3 into Eq. 6, and solving the resulting inequality for glide slope deviation, results in the following expression for the longitudinal window:

$$-1.05\tilde{\dot{h}}_{100} - 2.15u_{100} + d_2 \leq d_{100} \leq d_1 - 2.15u_{100} - 1.05\tilde{\dot{h}}_{100} \tag{7}$$

where $d_1 = 34 \text{ ft} - 1.15\hat{u}_w - 1.9(\partial u_w/\partial h) + 0.06(\partial u_w/\partial h)^2$

and $d_2 = d_1 - 75 \text{ ft}$

In order to gain a better insight regarding characteristics of the window, consider the case where $\tilde{h}_{100}$ is zero, so that a two-dimensional window results. The boundaries of the resulting window are sketched in Fig. 9 for the case of zero wind. (When a more complete set of constraints is considered, a more complete set of decision height boundaries results, as indicated in Fig. 10. However, inclusion of these other constraints will be deferred until later.) For situations involving head- and tail-winds and shears, d_1 and d_2 take on different values than those shown in Fig. 9. Thus the acceptable region (in Fig. 9) shifts up or down depending on the wind conditions. Values of d_1 and d_2 for the wind conditions specified in Ref. 2 are listed in Table 3 to give an indication of the sensitivity of the airplane-plus-controller to wind. The most critical of these wind conditions are seen to be the tailwind shear situation (which gives the maximum value of d_2) and the headwind shear <u>or</u> steady tailwind conditions (which both give about the same minimum value of d_1). The decision height boundaries corresponding to these critical wind situations are shown in Fig. 11. (It is recognized that the upper boundary corresponds to a different wind condition than the lower boundary, but for a window definition that doesn't depend on the existing wind conditions during an approach it is necessary to take the overall worst cases as the determining factors.) As seen in Fig. 11 the current Category II longitudinal approach window fits very nicely into the limits obtained for the individual critical wind and shear cases.

TABLE 3

VALUES OF d_1 AND d_2 FOR SEVERAL WIND CONDITIONS

WIND	d_1 (FT)	d_2 (FT)
Zero	34	−41
25 kt headwind	48.4	−26.6
10 kt tailwind	22.5	−52.5
+8 kt/100 ft (headwind) shear	22.6	−52.4
−8 kt/100 ft (tailwind) shear	53.0	−22.0

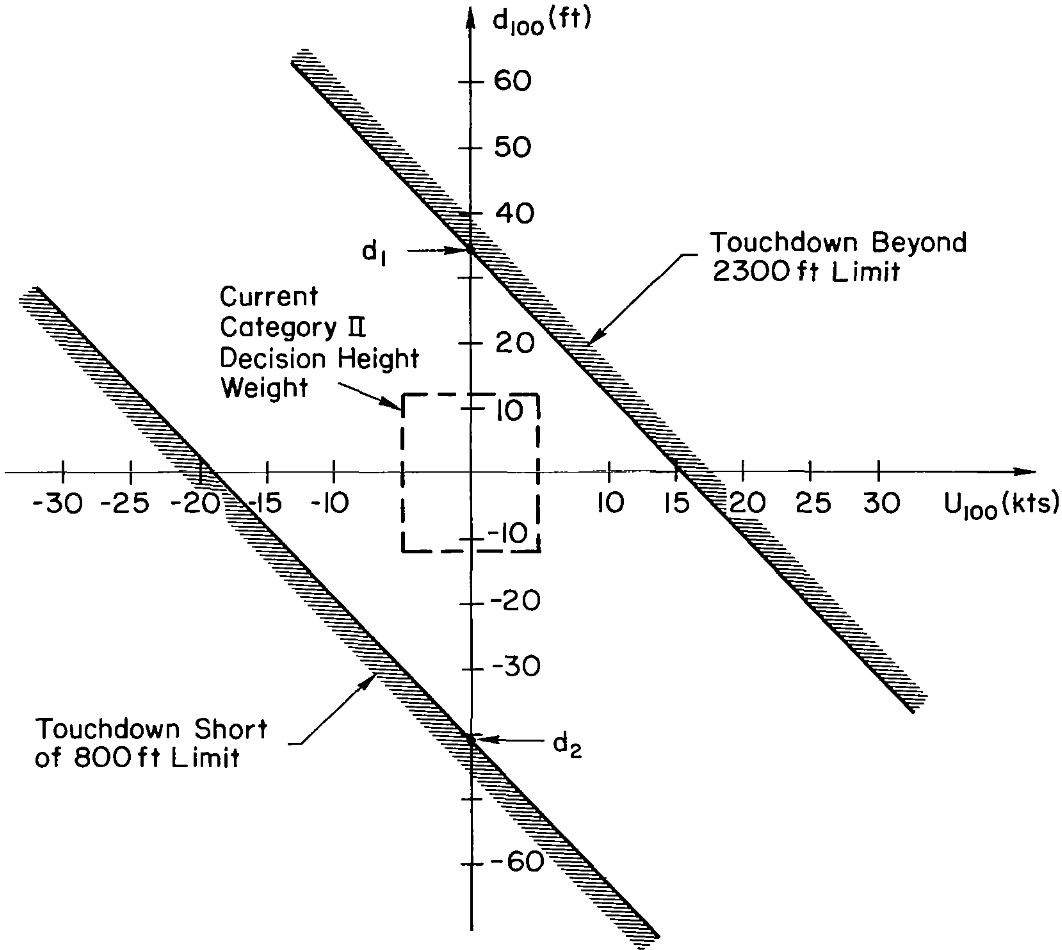

Figure 9. Longitudinal Decision Height Boundaries Based on FAA 2σ Limits on X_{TD} (with Zero Wind; and $\tilde{h}_{100} = 0$)

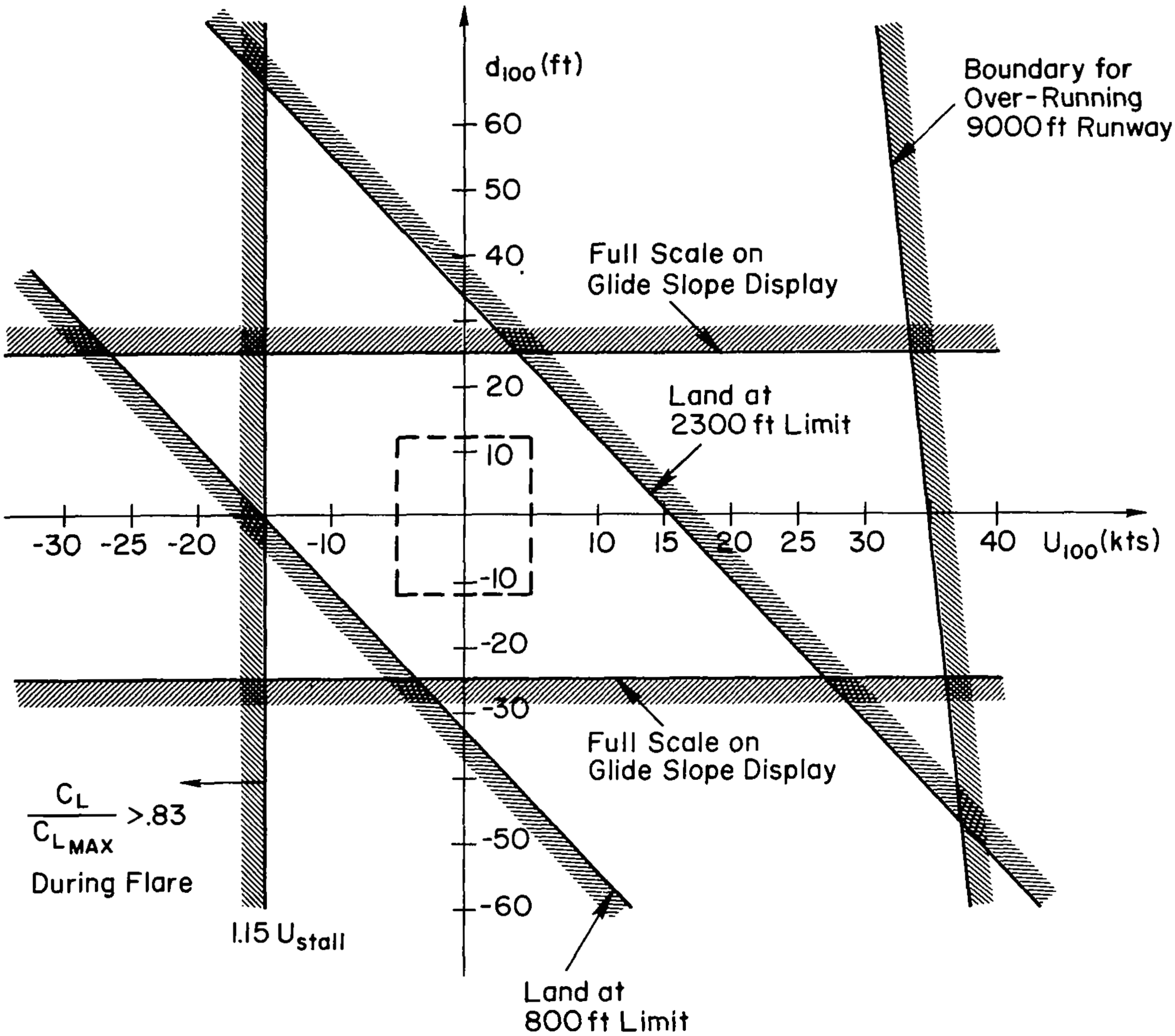

Figure 10. Longitudinal Decision Height Boundaries Based On A More Complete Set of Constraints (with Zero Wind; and $\tilde{h}$ = 0)

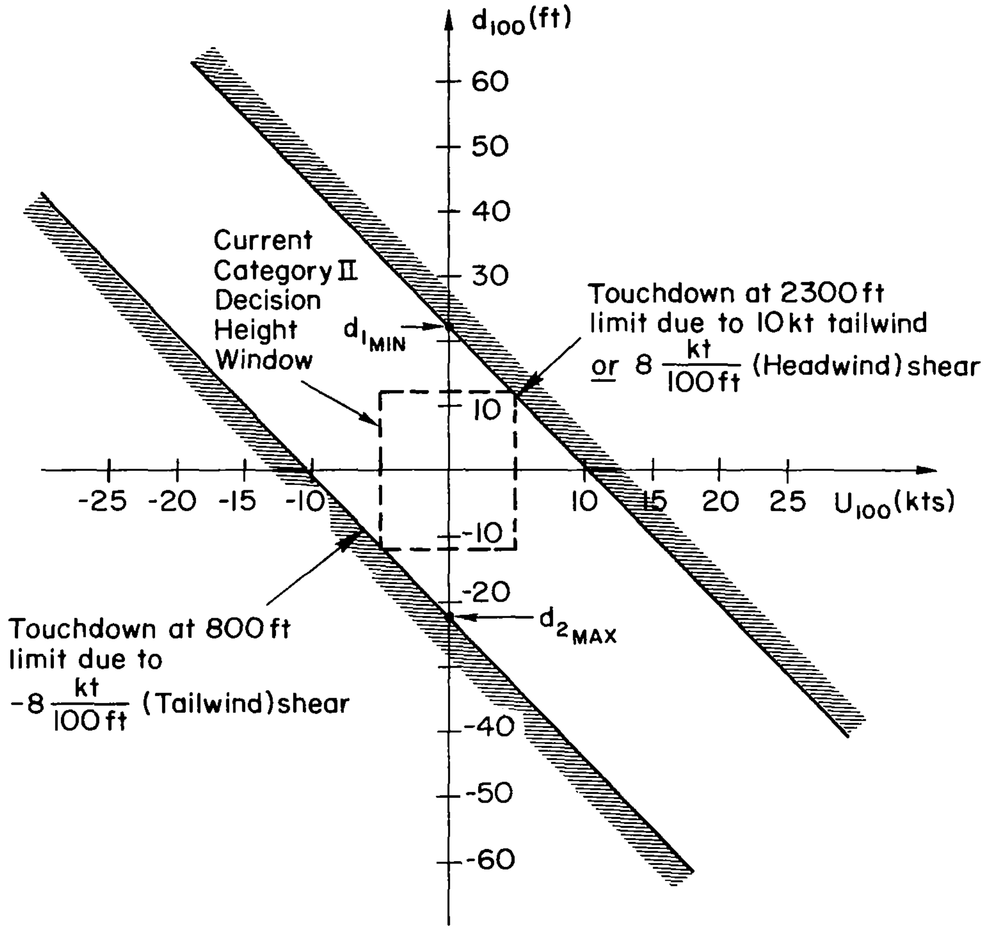

Figure 11. Longitudinal Decision Height Boundaries Based On FAA 2σ Limits on X_{TD} (with Individual Critical Winds; and $\tilde{h}_{100} = 0$)

At this point the question might be raised as to whether the current window is too conservative (in that a number of "safe" approaches would be outside the window and therefore aborted via missed approaches). The answer is a qualified yes. Referring to Fig. 11 it is seen that the current window comprises only a small part of the acceptable region. Even when other constraints (such as those shown in Fig. 10) are considered, the current window is a lot smaller than the acceptable region. Clearly it would be to everyone's benefit to make better use of the acceptable region. But the problem is in being able to determine whether or not an airplane is within the acceptable region as it passes through the decision height. This is the reason for the qualified answer. During an approach that is outside the current window and yet still within some larger window, the determination of the airplane's exact state is very difficult for a human pilot to accomplish. This is due in part to the moving needles (of the displays) as well as to the jostling cockpit environment that is undoubtedly present on an approach that is outside the current window. However, even without a dynamic environment, the pilot's ability to rapidly compute the tradeoff between excess altitude and a deficiency in airspeed (for example) is questionable. On the other hand, it would be a relatively simple matter to include a missed approach computer in the airplane to perform the calculations indicated in Eqs. 3 and 7 (along with a few additional obvious constraints) and display a predicted value of X_{TD} for the existing wind conditions, as well as a go/no-go decision for executing a missed approach. With such a device on board, better use could be made of the acceptable window conditions, resulting in fewer missed approaches as well as fewer accidents. More discussion of this concept will be presented later.

Before going on, a clarification concerning the orientation of the decision height window should be brought out. The various figures depicting the acceptable region at the decision height have all had the d_{100} axis pointing up. This is convenient for visualization purposes because the d variable is essentially a vertical displacement quantity. However, this may lead to a misconception of the actual geometric window in space that an airplane must pass through. Because a decision height window is <u>at</u> the decision height, it is actually a <u>horizontal</u> window, as shown in Fig. 12. Thus, even though an airplane may be above or below the center

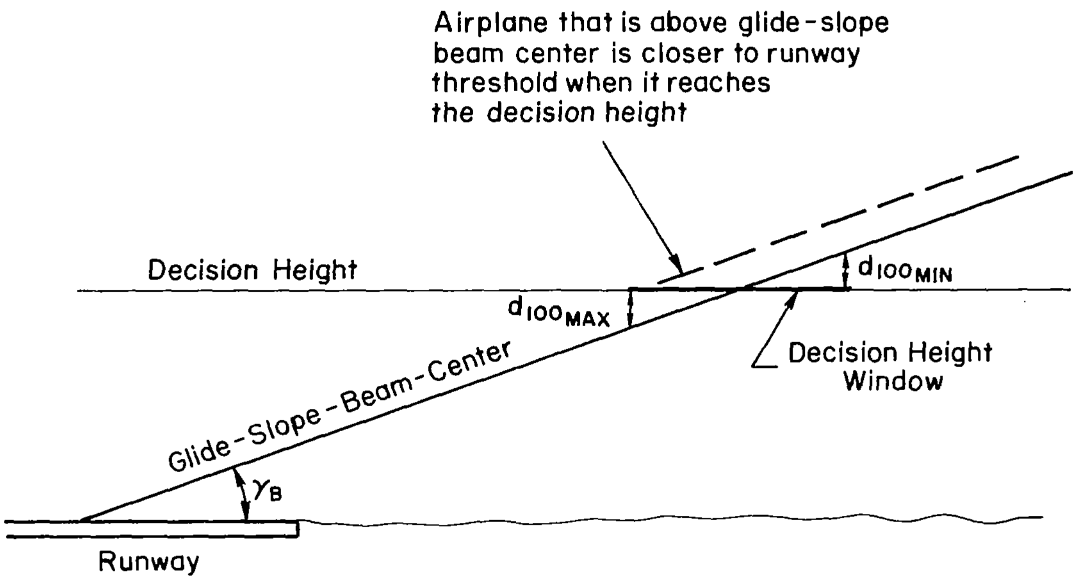

Figure 12. Relation Between Decision Height Window and Maximum Allowable Deviations Above and Below the Glide Slope Beam

of the glide slope beam, the decision height remains the same (100 ft above the runway elevation for ILS Category II). This means that if an airplane is above (or below) the beam, then it must be closer to (or farther from) the runway threshold when it reaches the decision height. In other words, what appears to be a vertical deviation from some point on the beam should really be thought of as a horizontal deviation from a different point on the beam (a point that is at the same altitude as the airplane). The relation between an "apparent" vertical deviation from the beam and the more appropriate horizontal deviation is just the tangent of beam angle. (In Eq. 3 the coefficient of d_{100} is $1/\tan \gamma_B \doteq 20$.)

Getting back to the earlier discussion, it is noted that all the figures depicting the window limits (in terms of d_{100} and u_{100}) have been drawn for $\tilde{\dot{h}}_{100} = 0$. The effect of a nonzero $\tilde{\dot{h}}_{100}$ is to raise or lower the acceptable region by an amount equal to $1.05\tilde{\dot{h}}_{100}$ (see Eq. 7). However, because the expected variation of $\tilde{\dot{h}}_{100}$ is small (of the order of 1 ft/sec or less) the maximum expected variations in window size and X_{TD} (due to $\tilde{\dot{h}}_{100}$) are also small (e.g., ΔX_{TD} is only 42 ft for a 2 ft/sec perturbation in $\tilde{\dot{h}}_{100}$). For such small variations in the touchdown location it is reasonable to ignore, for the time being, the effects of $\tilde{\dot{h}}_{100}$ in setting the acceptable window dimensions. A much more significant item to consider (when defining the limits of an acceptable window) is the possibility of encountering a <u>combination</u> of the wind inputs considered above.

By taking a combination of the 25 kt headwind and a −8 kt/100 ft (tailwind) shear (giving a decreasing headwind as an airplane descends), the values of d_1 and d_2 become 67.4 ft and −7.6 ft, respectively. This raises the lower decision height window boundary by 14.4 ft. If, in addition, the combination of a 10 kt tailwind and an 8 kt/100 ft headwind shear (i.e., a decreasing tailwind as an airplane descends) is also considered, then the upper decision height boundary is lowered by 11.4 ft (because this combination gives d_1 = 11.1 ft, and d_2 = −63.9 ft). By considering these additional wind input situations (which are the most severe as well as the most likely combinations to encounter), the critical decision height boundaries move closer together to become those shown in Fig. 13. Note that the current Category II window is no longer entirely within the acceptable region.

If, however, for these <u>critical combinations</u> of wind inputs the touchdown limits are relaxed from the 2σ values of 800 ft $\leq X_{TD} \leq$ 2300 ft, to the "hard" limits of 300 ft $\leq X_{TD} \leq$ 2550 ft, then the equations of d_1 and d_2 become

$$d_1 = 46.5 - 1.15\hat{u}_w - 1.9\frac{\partial u_w}{\partial h} + 0.06\left(\frac{\partial u_w}{\partial h}\right)^2$$

and

$$d_2 = d_1 - 112.5 \tag{8}$$

which give (for these particular input combinations)

$$\left.\begin{aligned} d_1 &= 79.9 \text{ ft} \\ d_2 &= -32.6 \text{ ft} \end{aligned}\right\} \text{for a 25 kt headwind decreasing at 8 kt/100 ft as you descend} \tag{9}$$

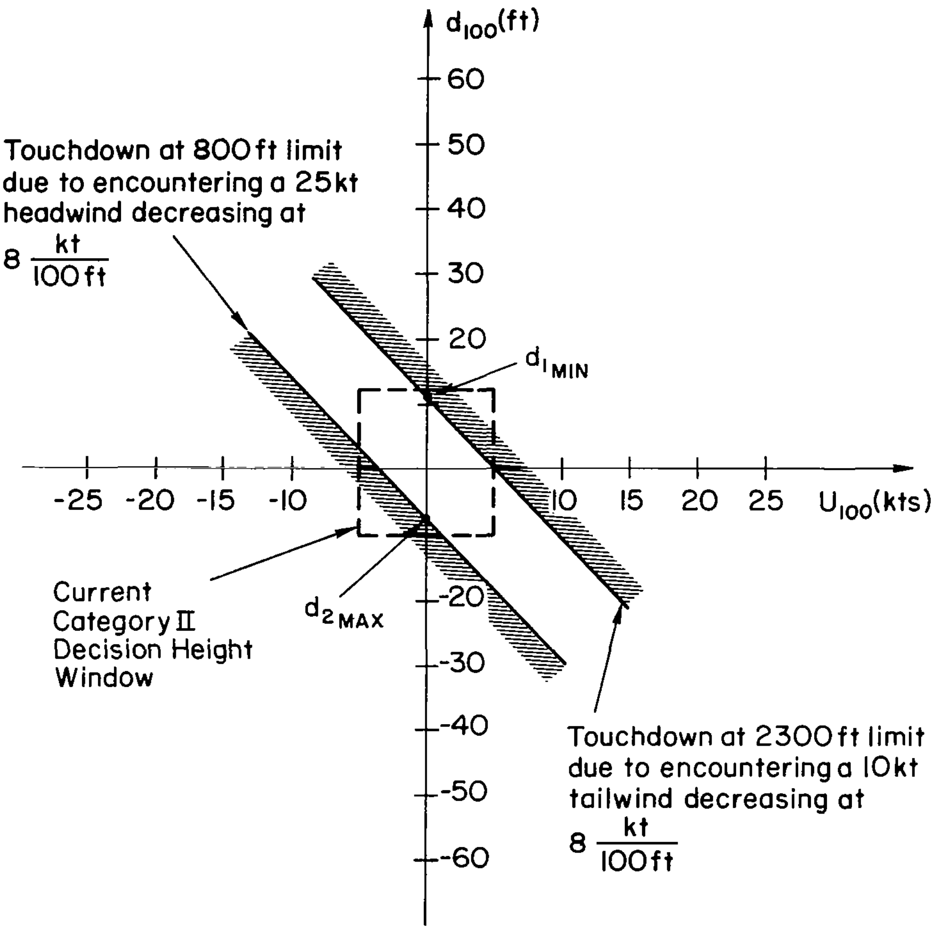

Figure 13. Longitudinal Decision Height Boundaries Based On FAA 2σ Limits on X_{TD} (with Critical Wind Combinations; and $\tilde{h}_{100} = 0$)

and

$$\left.\begin{aligned} d_1 &= 23.6 \text{ ft} \\ d_2 &= -88.9 \text{ ft} \end{aligned}\right\} \quad \begin{array}{l}\text{for a 10 kt tailwind} \\ \text{decreasing at 8 kt/100 ft} \\ \text{as you descend}\end{array} \qquad (10)$$

Taking the critical values of d_1 and d_2 from the above equations results in the decision height boundaries moving apart, as shown in Fig. 14. It is seen in Fig. 14 that the current Category II decision height window lies completely within the window limits corresponding to the "hard" touchdown position limits. However, in order to justify using the "hard" limits (rather than the 2σ limits) it is necessary to consider the probabilities of encountering the various steady winds and wind shears. But this is beyond the scope of the present study. Therefore, the following reasoning seems appropriate. Because the most severe combination of wind inputs still results in a safe touchdown (longitudinally), it will be assumed that the current Category II longitudinal window is acceptable for our example system (although maybe not optimum).

Having considered some of the various factors affecting the longitudinal touchdown situation, some conclusions can be drawn regarding an acceptable decision height window. If a human pilot is the sole monitor and decision maker, then <u>no</u> "calculations" should be required of him to determine whether or not the airplane is within the acceptable window at the decision height. This means there must be a hard limit on each of the decision height window variables (rather than allowing an excess in one variable to compensate for a deficiency in another). This is the current situation, and results in a rectangular window as shown in Fig. 14 (for example). On the other hand, if an electronic monitor is available to make the required calculations, then the acceptable decision height window should take advantage of the entire acceptable region (or at least more of it than is used at present), thereby lowering the missed approach rate. As an added benefit, the electronic monitor will also be a faster and more accurate judge of the airplane's situation at the decision height.

Based on the results shown in Figs. 11 and 14, one might conclude that for human pilot monitoring the current Category II longitudinal decision height window (±12 ft of glide slope deviation and ±5 kt of airspeed error) is the appropriate longitudinal window for the example

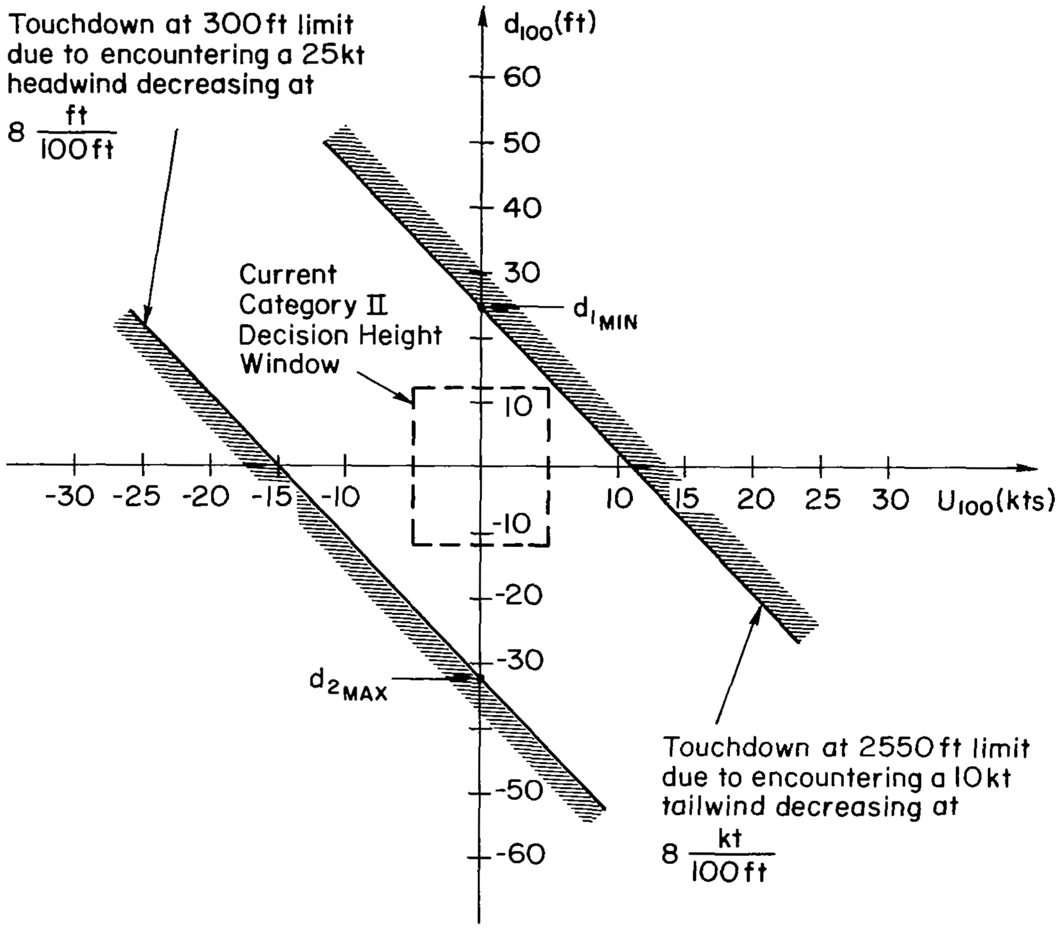

Figure 14. Longitudinal Decision Height Boundaries Based on "Hard" FAA Limits on X_{TD} of: 300 ft $\leq X_{TD} \lesssim$ 2550 ft (With Critical Wind Combinations; and $\dot{h}_{100} = 0$)

airplane-plus-controller used in this study. Conveniently, the current ±12 ft window happens to coincide with a half-scale (or one dot) deviation on the glide slope display, making it a simple matter to judge acceptable errors from excessive errors. (It is noted that to increase the window size by adding an extra foot or so to the acceptable glide slope beam deviations would make the decision process significantly more difficult because it would then require the pilot to judge needle widths and fractions of dots on the glide slope display.) However, such a conclusion will <u>not</u> be made at this time. Before any conclusion is drawn for a human pilot monitor, the distribution of the expected initial conditions at the decision height should be considered. In this way tradeoffs among the window limits can be made in order to achieve an optimum window (i.e., one that results in fewer overall missed approaches). Such considerations are presented in Section IV.

If, however, an electronic monitor is used, then the decision height window would be that shown in Fig. 15, which is essentially a repeat of Fig. 11 with additional constraints added. The additional constraints are that the glide slope display must not exceed a full-scale (or two dot) deviation, and the airspeed must not go below 1.15 u_{stall}. The glide slope deviation constraint is used to enable the pilot to estimate the airplane's deviation from the beam center (rather than the display just showing him that the needle is pinned, and therefore that he is way off the beam), and the speed constraint is used to insure that a margin of maneuver capability is always available (see appendix).

B. LATERAL CONSIDERATIONS

The technique used to generate a lateral window at the decision height is the same as that used for the longitudinal window. First it is determined which lateral variables have a significant correlation between their decision height values and touchdown conditions. For the example system these turned out to be y_{100} and $\dot{y}_{100}$. Then, for all reasonable values of initial conditions at the decision height and wind and shear inputs from the decision height down to the ground, all the lateral touchdown variables that come close to their respective limiting acceptable values are

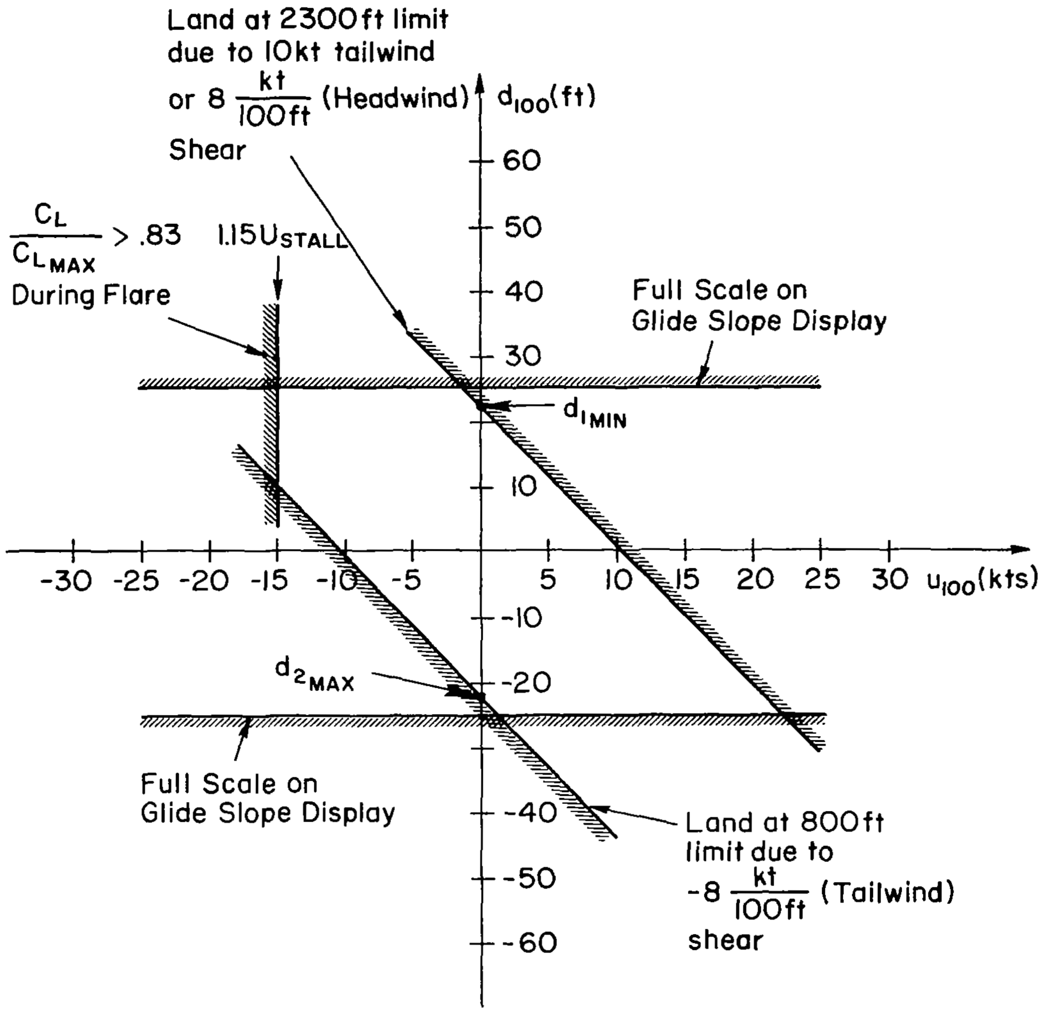

Figure 15. Longitudinal Decision Height Boundaries For System With An Electronic Monitor — Based On FAA 2σ Limits on X_{TD} (With Individual Critical Winds; and $\tilde{h}_{100} = 0$)

determined. For the example system these are y_{TD} and $\dot{y}_{TD}$. The wind inputs considered are those listed in Ref. 2.

- Steady crosswind of 15 kt
- Crosswind shear of 8 kt/100 ft

It turns out that the lateral touchdown position also depends on the longitudinal flare time. This dependence is accounted for by considering the minimum, nominal, and maximum flare times (8.7, 12.3, and 14.9 sec) obtained in the longitudinal analyses, and then using the most critical one for each constraint. Plots of y_{100} and $\dot{y}_{100}$ versus y_{TD} and $\dot{y}_{TD}$ (four plots) were obtained for zero wind, steady crosswind, and crosswind shear situations. Each plot consisted of a family of three curves representing the variation in longitudinal flare time.

For the zero wind case the short flare time (8.7 sec) was the most critical, in that it gave the largest touchdown dispersions for initial conditions of y_{100} and $\dot{y}_{100}$. Empirical equations for the touchdown state (in terms of initial conditions) were obtained from curve-fits to the analog computer traces. The results are given as follows:

$$y_{TD} = 0.33y_{100} + 4.6\dot{y}_{100} \tag{11}$$

$$\dot{y}_{TD} = -0.09y_{100} - 0.05\dot{y}_{100} \tag{12}$$

Substituting the appropriate limits from the appendix ($|y_{TD}| < 27$ ft, and $|\dot{y}_{TD}| < 8$ ft/sec) into Eqs. 11 and 12 gives the inequalities which define the lateral window for the zero wind condition.

$$-81 - 13.8\dot{y}_{100} < y_{100} < 81 - 13.8\dot{y}_{100} \tag{13}$$

$$-88 - 0.57\dot{y}_{100} < y_{100} < 88 - 0.56\dot{y}_{100} \tag{14}$$

The lateral decision height window represented by these inequalities is shown in Fig. 16.

It is interesting to note that this no-wind window is essentially the same as the current Category II window, if a particular interpretation of

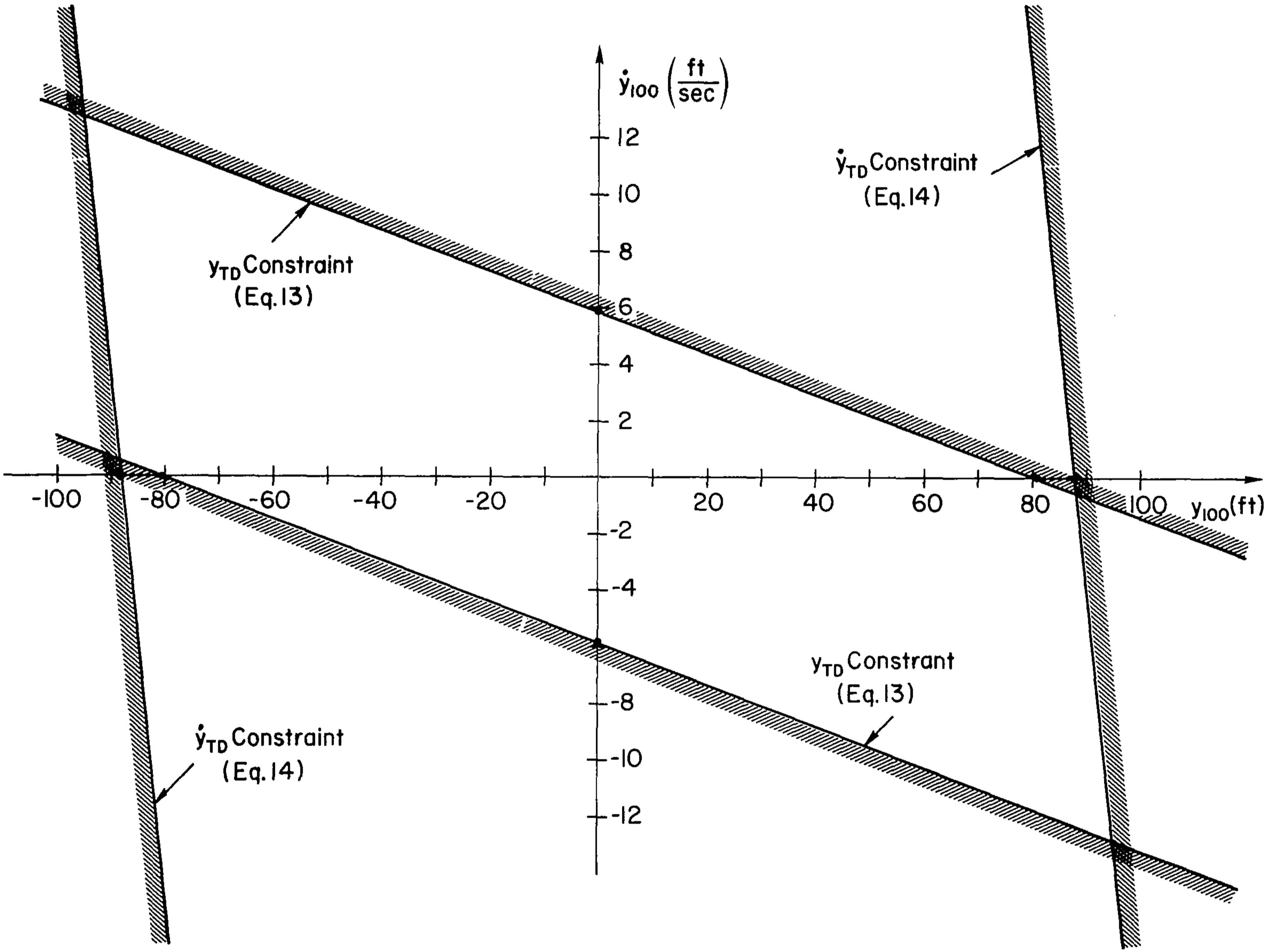

Figure 16. Lateral Decision Height Window For Zero Wind

the FAA's verbal description of the current window is used. Reference 1 states as part of the definition of a successful approach: "The airplane is positioned so that the cockpit is within, and tracking so as to remain within, the lateral confines of the runway extended." For the airplane to be within the confines of the runway extended means a ±75 ft maximum localizer deviation (for a standard 150 ft wide runway). To be tracking so as to remain within the lateral confines of the runway can be interpreted to mean that the combination of current lateral deviation and lateral deviation rate (at the decision height) results in a projected touchdown point that is still on the runway. Figure 17 shows a graphic example of this concept, while the following equations express these constraints mathematically (for the nominal flare time).

$$-75 < y_{100} < 75 \tag{15}$$

and

$$-75 - 12.3\dot{y}_{100} < y_{100} < 75 - 12.3\dot{y}_{100} \tag{16}$$

Figure 18 is a repeat of Fig. 16 with the current decision height window (expressed via Eqs. 15 and 16) superimposed for comparison.

Because the steady crosswind situation gave significantly smaller touchdown dispersions than the crosswind shear situation, only the shear situation was considered in the window calculations.

The crosswind shear input resulted in the largest lateral touchdown position errors being associated with the long flare time, and the largest touchdown drift rates with the short flare time. Expressions giving the pertinent touchdown variables for these critical situations are:

$$y_{TD} = 22 + 0.08y_{100} + 3.8\dot{y}_{100} \tag{17}$$

$$\dot{y}_{TD} = 3 - 0.1y_{100} \tag{18}$$

Substituting the y_{TD} and $\dot{y}_{TD}$ limits into these equations results in the following inequalities which define the window for the +8 kt/100 ft windshear input.

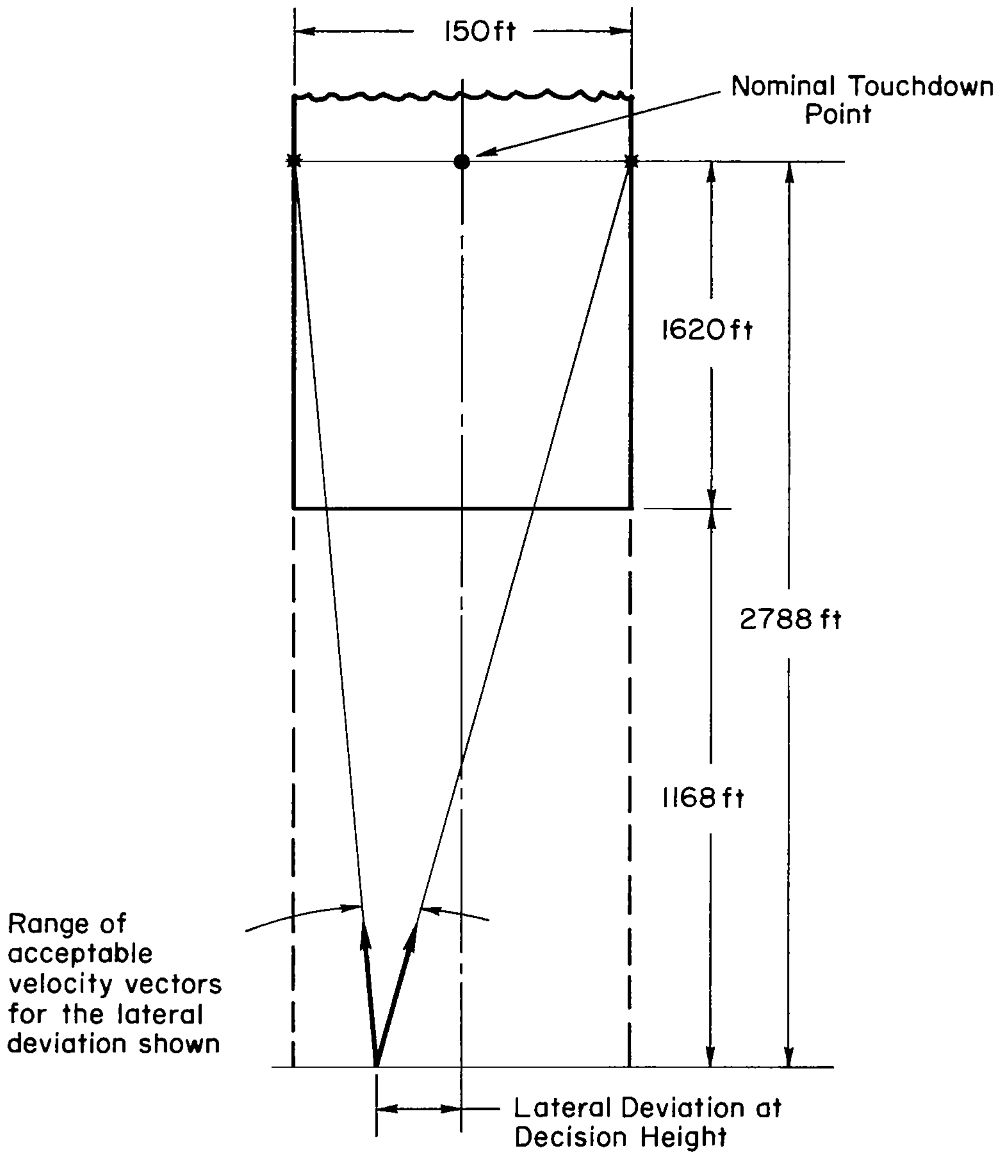

Figure 17. Example of A Lateral Deviation and The Associated Deviation Rates (At Decision Height) That Result In A Projected Touchdown Point Within The Runway Confines

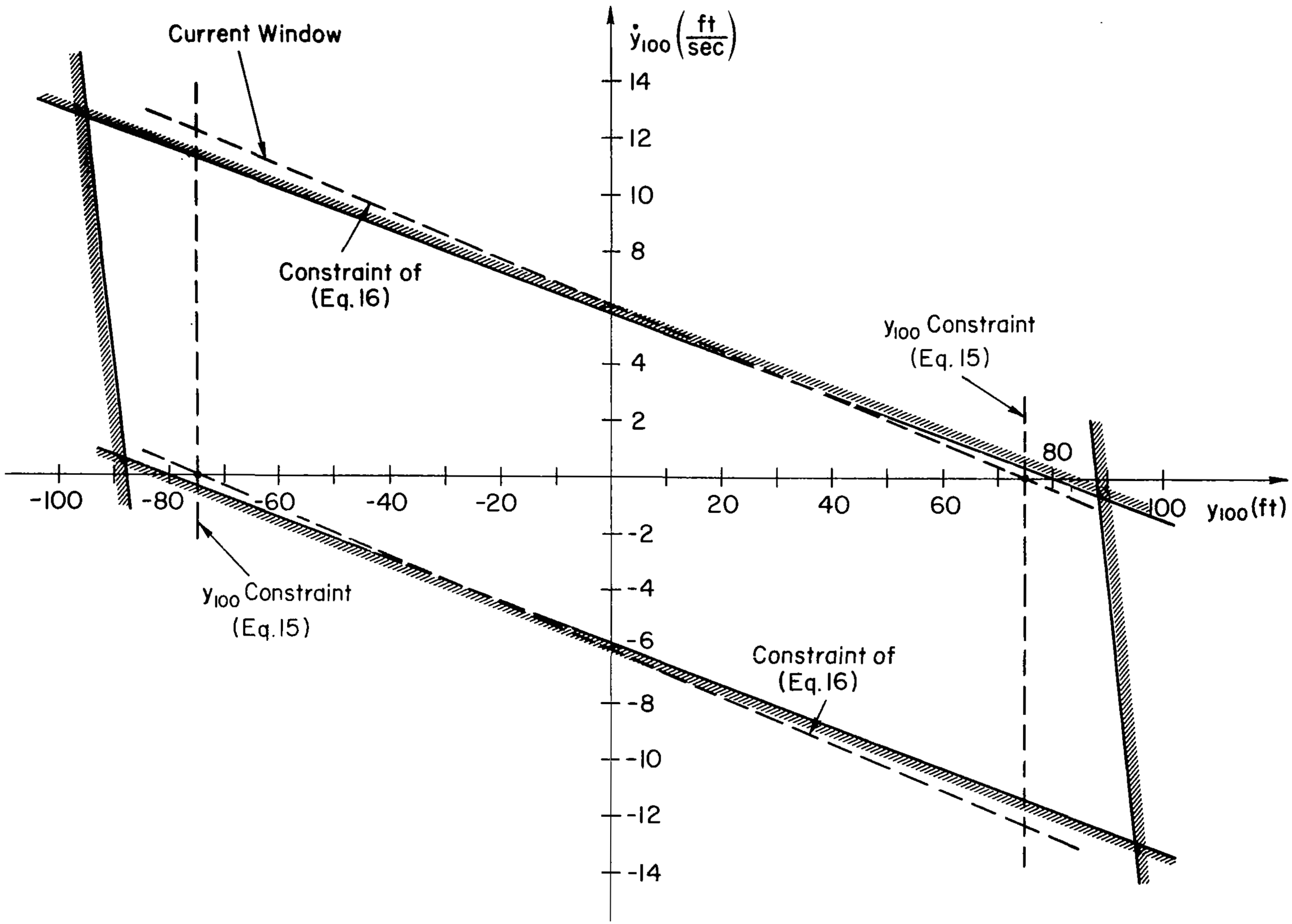

Figure 18. Lateral Decision Height Window For Zero Wind, With Current Window Constraints Superimposed

$$-12.9 - 0.021y_{100} < \dot{y}_{100} < 1.3 - 0.021y_{100} \tag{19}$$

$$-50 < y_{100} < 110 \tag{20}$$

The resulting window is shown in Fig. 19. However, because the wind shear may come from either direction, it is necessary to define the acceptable decision height region as that bounded by the closest boundaries shown in Fig. 19, and their axially symmetric images. The resulting region is shown in Fig. 20.

It is clear from Fig. 20 that the ±27 ft touchdown limits result in an extremely small decision height window; one that is too restrictive except in the presence of a large wind shear. However, because this magnitude of lateral wind shear does not occur very often, it seems reasonable to relax the ±27 ft limit on y_{TD} for such a shear condition. This seems especially appropriate because the 27 ft limit is a 2σ value and not a hard limit. As was the case with the longitudinal situation, the probability of occurrence of crosswind shears would have to be known to perform a precise analysis. However, in the absence of such data, the course taken here is to expand the acceptable lateral touchdown limits for the crosswind shear situation to ±43 ft. This number is arrived at as follows.

The hard limit for an acceptable lateral touchdown dispersion is given in Ref. 2 (and the appendix) as when the outboard landing gear is no closer than 5 ft from the lateral limits of a 150 ft wide runway. For a DC-8 this corresponds to $|y_{TD}| < 58$ ft. By providing an additional 15 ft cushion (admittedly somewhat arbitrary), a 20 ft margin is obtained between the outboard landing gear and the runway edge for the large crosswind shear situation.

As seen in Fig. 21, the decision height window for $|y_{TD}| < 43$ ft is considerably larger than the window defined for $|y_{TD}| < 27$ ft. However, an additional constraint on the allowable touchdown conditions is now appropriate. If $\dot{y}_{TD} = 8$ ft/sec when $y_{TD} = 27$ ft, then the time to reach the runway edge is 4.5 sec $[= (63 - 27)/8]$ if no control is used. Maintaining the same 4.5 sec margin for touchdowns beyond 27 ft from the centerline gives an additional constraint. Thus, for the case of running

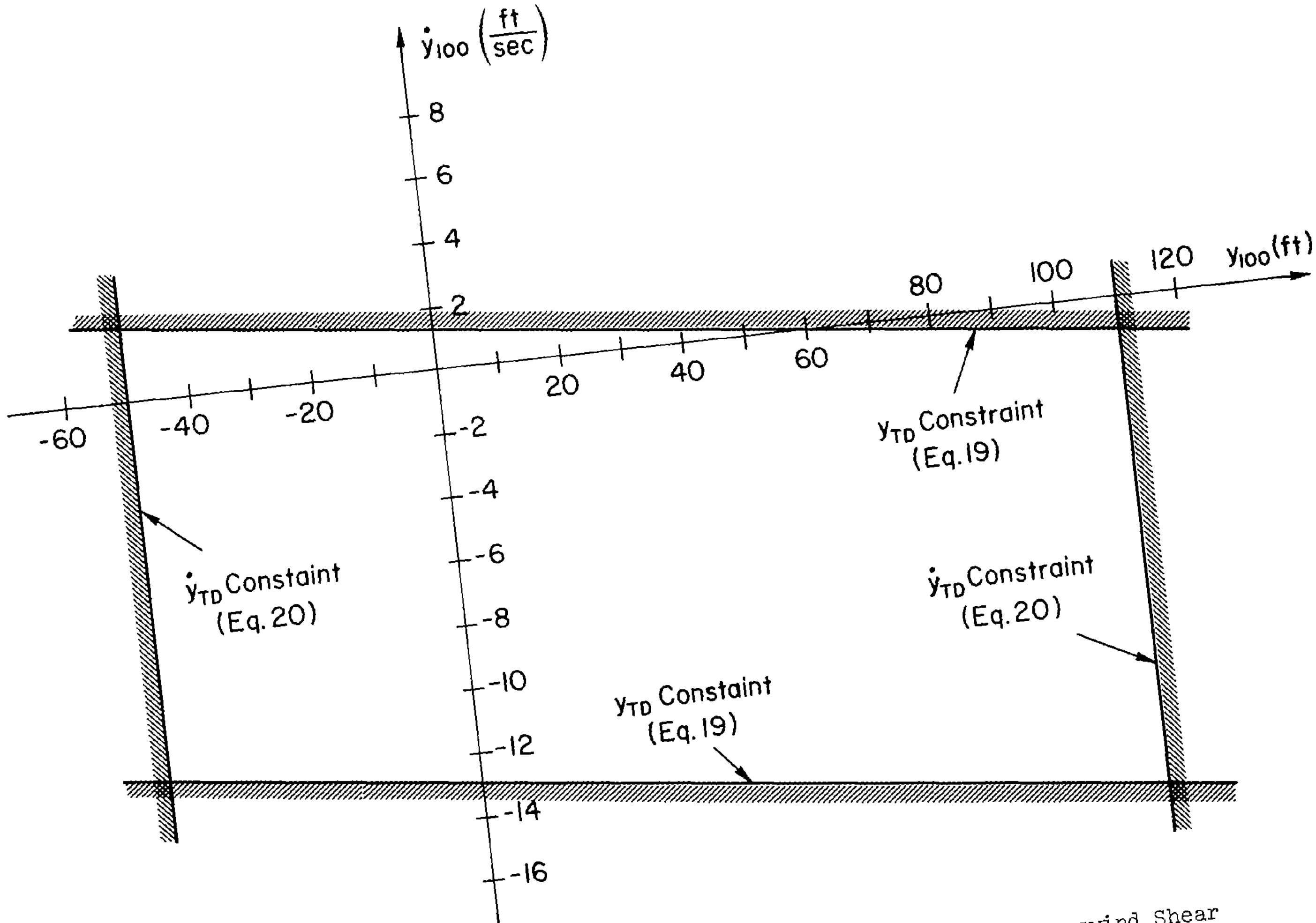

Figure 19. Lateral Decision Height Window for −8 kt/100 ft Crosswind Shear (Increasing Wind From Left As Airplane Descends)

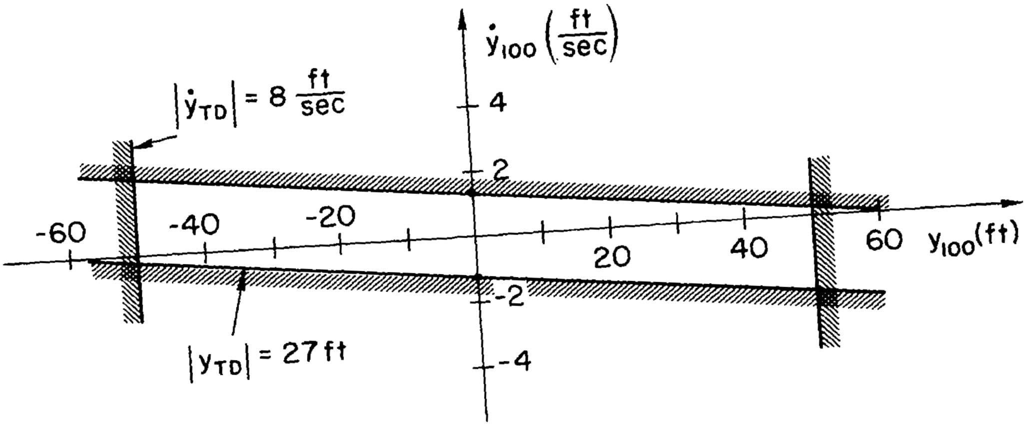

Figure 20. Lateral Decision Height Window For ±8 kt/100 ft Crosswind Shear

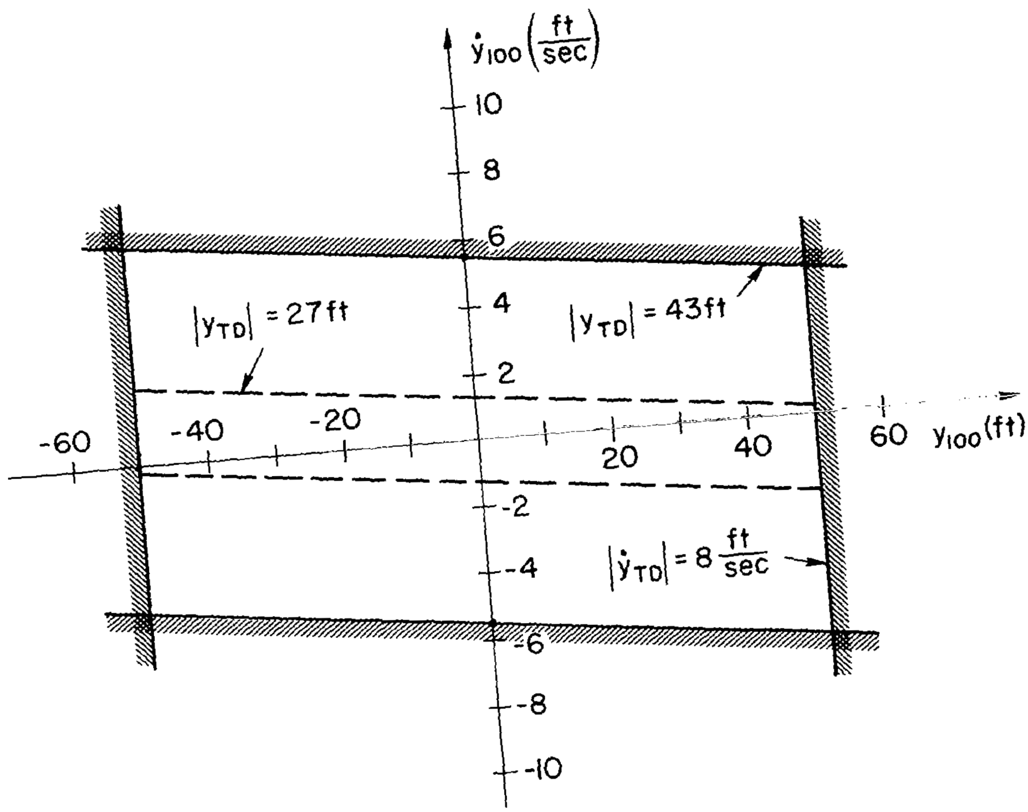

Figure 21. Modified Lateral Decision Height Window for ±8 kt/100 ft Crosswind Shear

off the right side of the runway with an increasing crosswind from the left, the following constraint is appropriate:

$$\frac{63 - y_{TD}}{\dot{y}_{TD}} > 4.5 \tag{21}$$

Substituting the expressions for y_{TD} and $\dot{y}_{TD}$ (given in Eqs. 17 and 18) into Eq. 21 leads to

$$\dot{y}_{100} < 7.2 + 0.1y_{100} \tag{22}$$

Adding this constraint and its axially symmetric counterpart (corresponding to running off the left side of the runway with a crosswind shear from the right) results in the acceptable decision height region shown in Fig. 22.

The hexagonal region shown in Fig. 22 would be an appropriate window if there were always a wind shear of 8 kt/100 ft. However, on most occasions there will be no such shear condition. This is brought up because the acceptable decision height region for the wind shear case is not totally within the acceptable region for the zero-wind case. This comes about because the ±27 ft limit on y_{TD} was relaxed to ±43 ft for the shear case, but remains ±27 ft for the zero-wind case. As a consequence, the acceptable region at the decision height (which is the region common to both the shear and zero-wind regions) is not just the acceptable region for the shear condition, but is that shown in Fig. 23.

The acceptable decision height region in Fig. 23 would be an appropriate window when using an electronic decision height computer. However, for a human pilot it is unacceptably complicated. The tradeoffs between lateral offset and drift rate could never be made very accurately. Therefore, a simpler window must be generated for a human decision maker. Per the discussion of the longitudinal window, the window must be rectangular. This will necessarily result in a smaller window, and will therefore generate more missed approaches. To select the rectangle that gives the fewest missed approaches requires a knowledge of the distributions of y_{100} and $\dot{y}_{100}$. Such considerations are presented in Section IV.

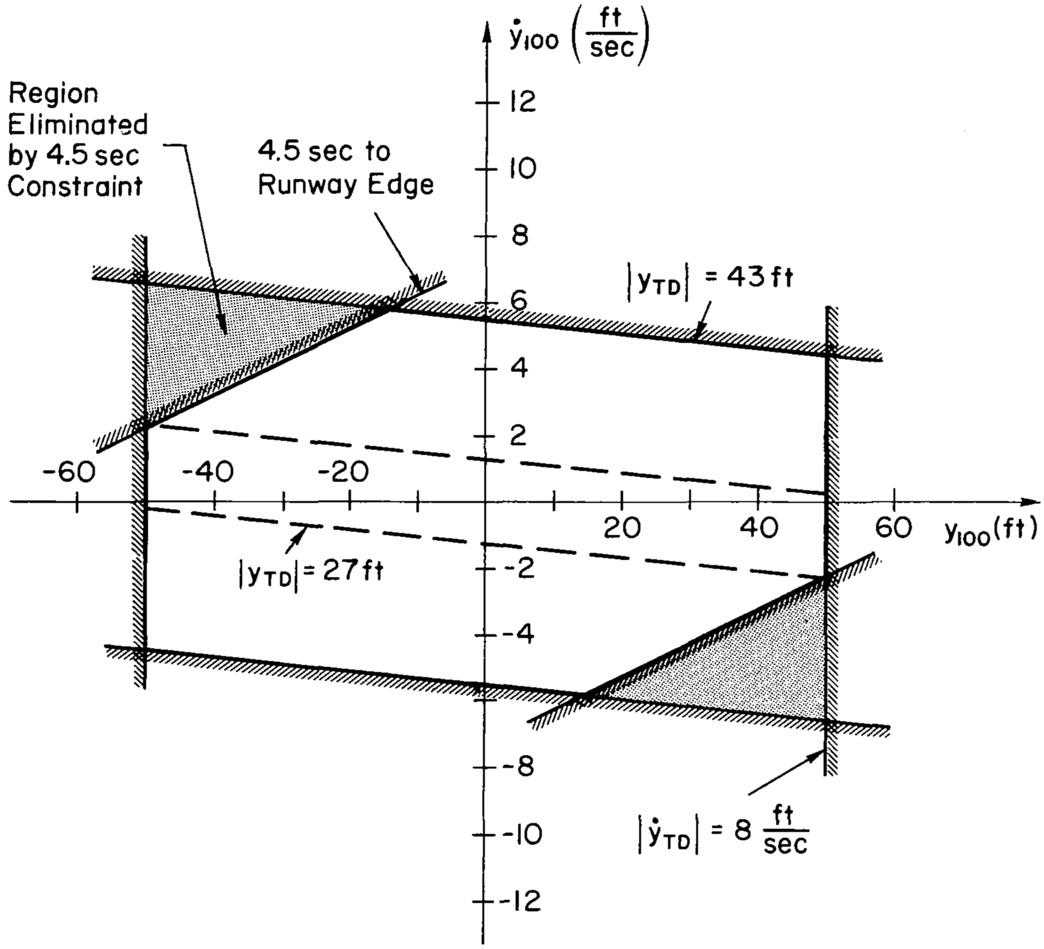

Figure 22. Modified Lateral Decision Height Window For A ±8 kt/100 ft Crosswind Shear, And A Constraint Requiring A Minimum Time Of 4.5 sec To Reach The Runway Edge After Touchdown

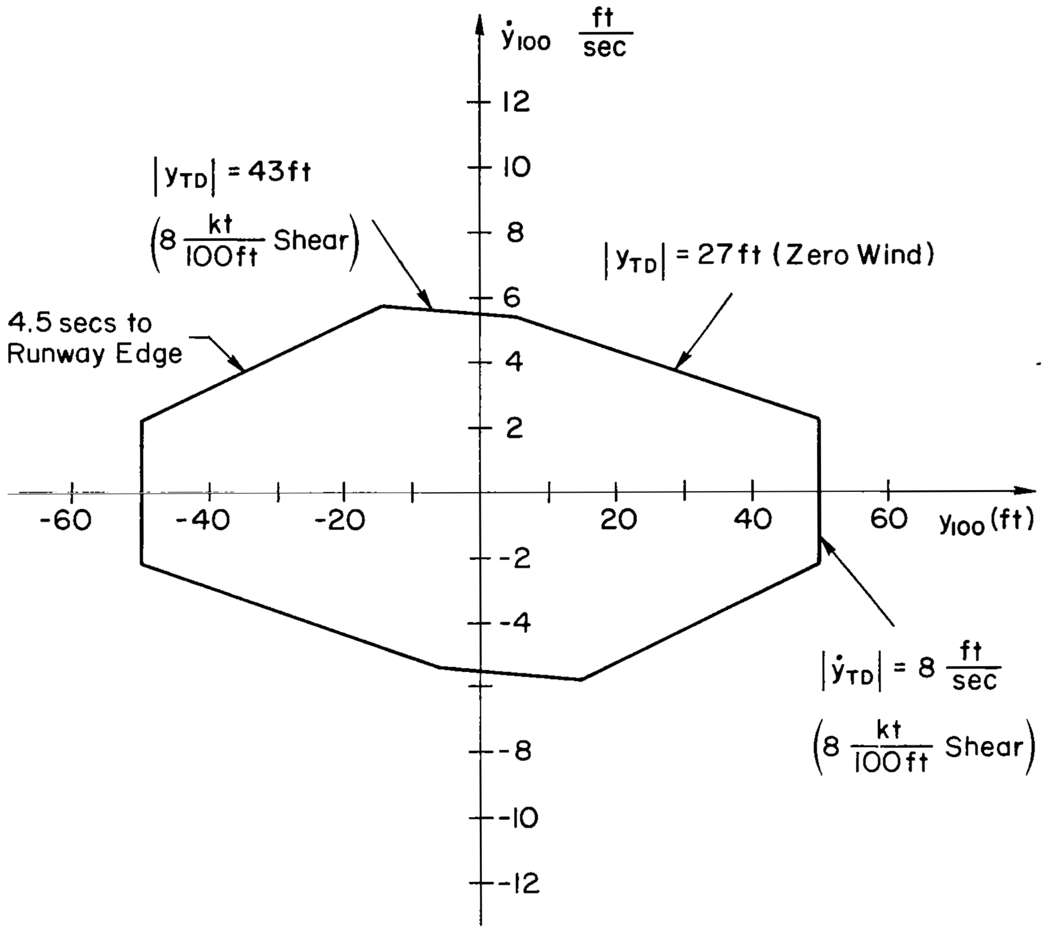

Figure 23. Acceptable Lateral Decision Height Region

Because so many different wind conditions, and 2σ and "hard" limits, have been considered in this section, a large number of figures depicting acceptable window limits have resulted. This might lead to some confusion in the reader's mind. If not, so much the better. But just to make sure, the final version of the longitudinal acceptable decision height region is repeated here as Fig. 24 for easy reference. Thus, Figs. 24 and 23 represent the acceptable longitudinal and lateral decision height regions (for $\tilde{h}_{100} = 0$).

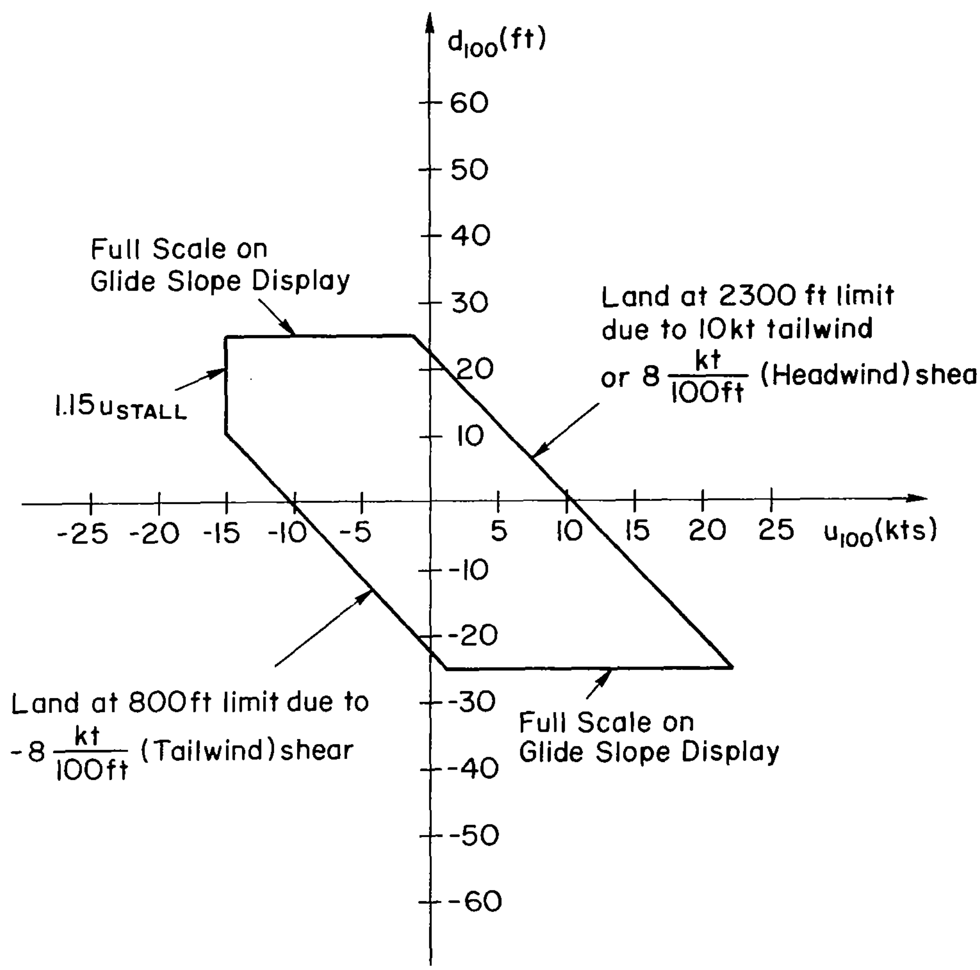

Figure 24. Acceptable Longitudinal Decision Height Region (for $\tilde{h}_{100} = 0$)

SECTION IV

ANALYSIS OF DECISION HEIGHT SITUATION, INCLUDING RESULTS FROM APPROACH DISPERSION CALCULATIONS

In Section III the maximum limits for the longitudinal and lateral decision height windows were computed and plotted (see Figs. 24 and 23). If an electronic decision height monitor is used, then these figures represent the decision height window (with the modification that $\tilde{h}_{100}$ would again be included, via Eq. 7). However, if a human pilot monitor is used, then one more step is required. This is because it is impractical to expect any tradeoff calculations among window parameters to be made by a human pilot monitor. Thus the longitudinal and lateral regions would have to be made rectangular (requiring only a "less-than" or "greater-than" decision by the pilot for each individual variable). The resulting rectangular window is obtained by fitting the "best" rectangle into each of the acceptable longidudinal and lateral regions. The question arises as to how to determine the "best" rectangles to use. This is simple to answer. The rectangles should be selected to give the least number of missed approaches. This is accomplished by selecting the rectangle boundaries to "match" the approach dispersions. That is, the sides of the rectangle are made to be proportional to the rms approach dispersions. Then the largest rectangle with that "shape" is fit into the acceptable region. This defines the decision height window for the human pilot monitor case. Longitudinal and lateral examples of this procedure are presented to demonstrate the steps required.

Before getting to these examples, it should be emphasized again that the windows we have been referring to are not actual geometrical windows in space, but a windows in "state space," which have the dimensions of $[d_{100}, u_{100}, \tilde{h}_{100}]$ and $[y_{100}, \dot{y}_{100}]$, respectively, for the longitudinal and lateral situations.

Using the techniques (and some of the results) from Ref. 8 leads to the following rms values at the decision height for a gust environment with $\sigma_{w_g} = 4$ ft/sec and $\sigma_{u_g} = \sigma_{v_g} \doteq 10$ ft/sec.

$$\sigma_{d_{100}} \doteq 5 \text{ ft}$$

$$\sigma_{u_{100}} \doteq 2 \text{ kt}$$

$$\sigma_{y_{100}} \doteq 20 \text{ ft}$$

$$\sigma_{\dot{y}_{100}} \doteq 3.5 \text{ ft/sec}$$

Using these numbers, Figs. 25 and 26 show the 2σ deviations for each variable superimposed on the acceptable regions (from Figs. 24 and 23). From these figures it is a simple matter to scale up (or down) the 2σ rectangles to just fit within the boundaries of the acceptable regions. The resulting "best" rectangular windows are shown in Figs. 27 and 28. In Fig. 28 it is seen that two corners of the rectangle are allowed to exceed the acceptable region by a small amount so that the other two corners can reach the limit of the acceptable region. This is considered acceptable because the corners correspond to y_{100} and $\dot{y}_{100}$ simultaneously reaching their limiting values (a very unlikely situation), and the boundary exceeded is the ±27 ft limit, which is only a 2σ constraint (and not a hard limit). Also included in these figures for comparison purposes are the current ILS Category II window boundaries.

Several conclusions are obvious from these figures. (Note that some of the conclusions are based on the assumed gust level.) First, 2σ longitudinal dispersions are entirely within the human-monitor rectangular window. This means that with the assumed gust level less than 5 percent of the approaches will result in missed approaches (due to longitudinal dispersions). Second, the longitudinal rectangular window is very easy for the pilot to monitor. The window limits correspond very closely to 1 dot (half-scale) of glide slope deviation and 5 kt of airspeed deviation. Third, the longitudinal rectangular window is essentially identical to the current Category II longitudinal window. This is undoubtedly a complete coincidence. Fourth, although the acceptable longitudinal region is considerably larger than the rectangular window, the fact that it would take more than a 2.4σ longitudinal dispersion to exceed the rectangular window means that only about 1.5 percent of the approaches will result in missed

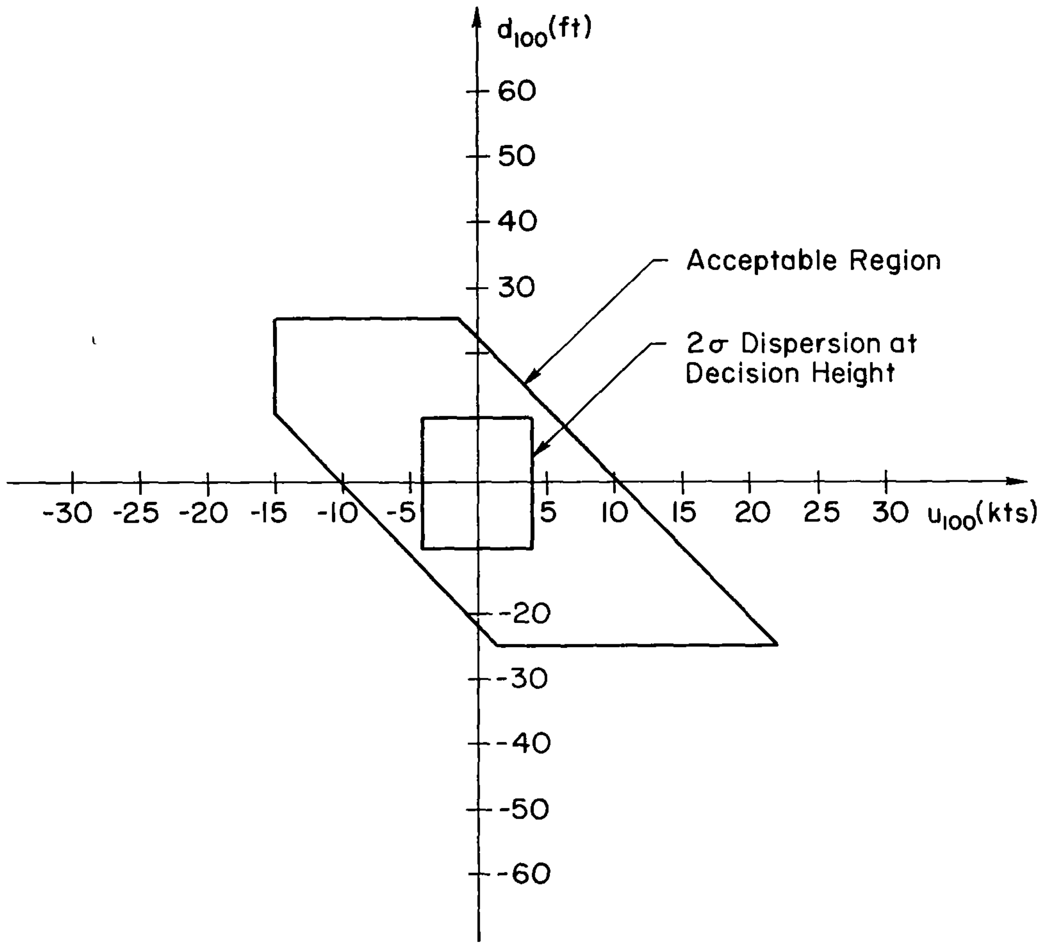

Figure 25. 2σ Longitudinal Dispersions at Decision Height, with Acceptable Decision Height Boundaries Superimposed

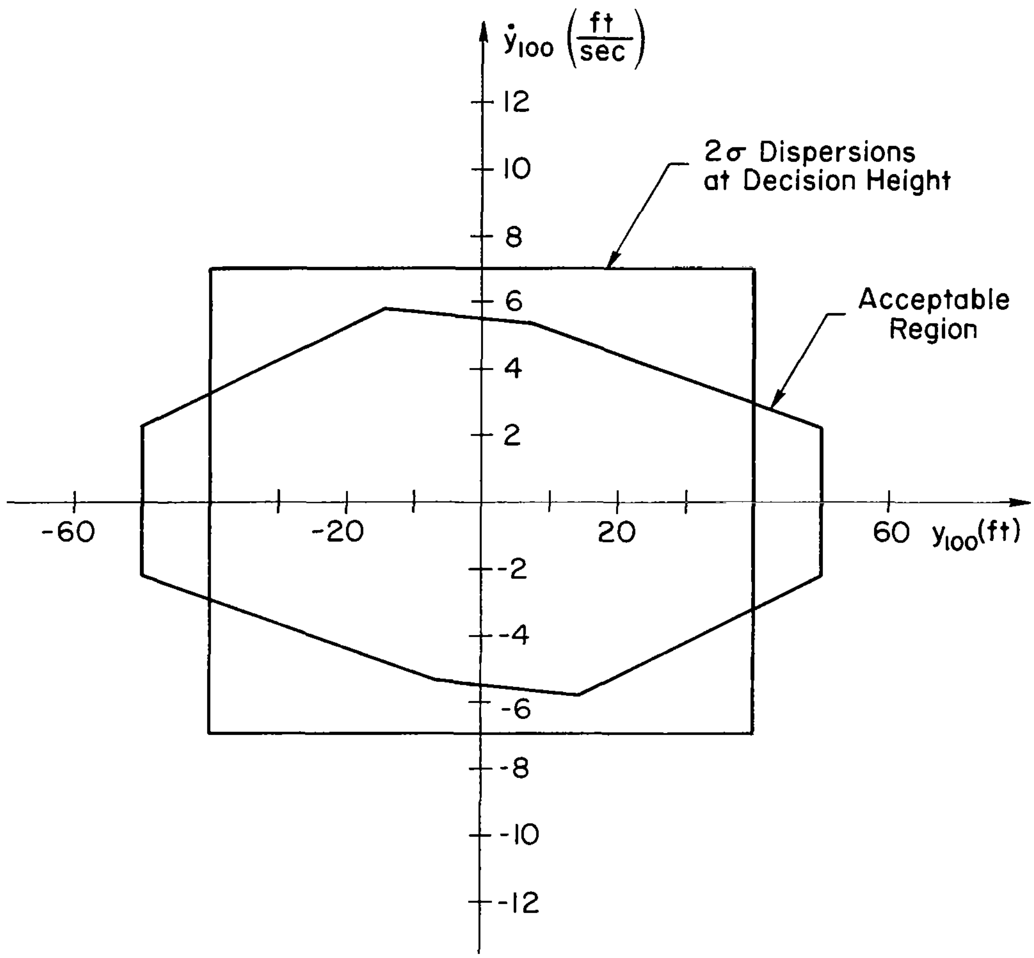

Figure 26. 2σ Lateral Dispersions at Decision Height, with Acceptable Decision Height Boundaries Superimposed

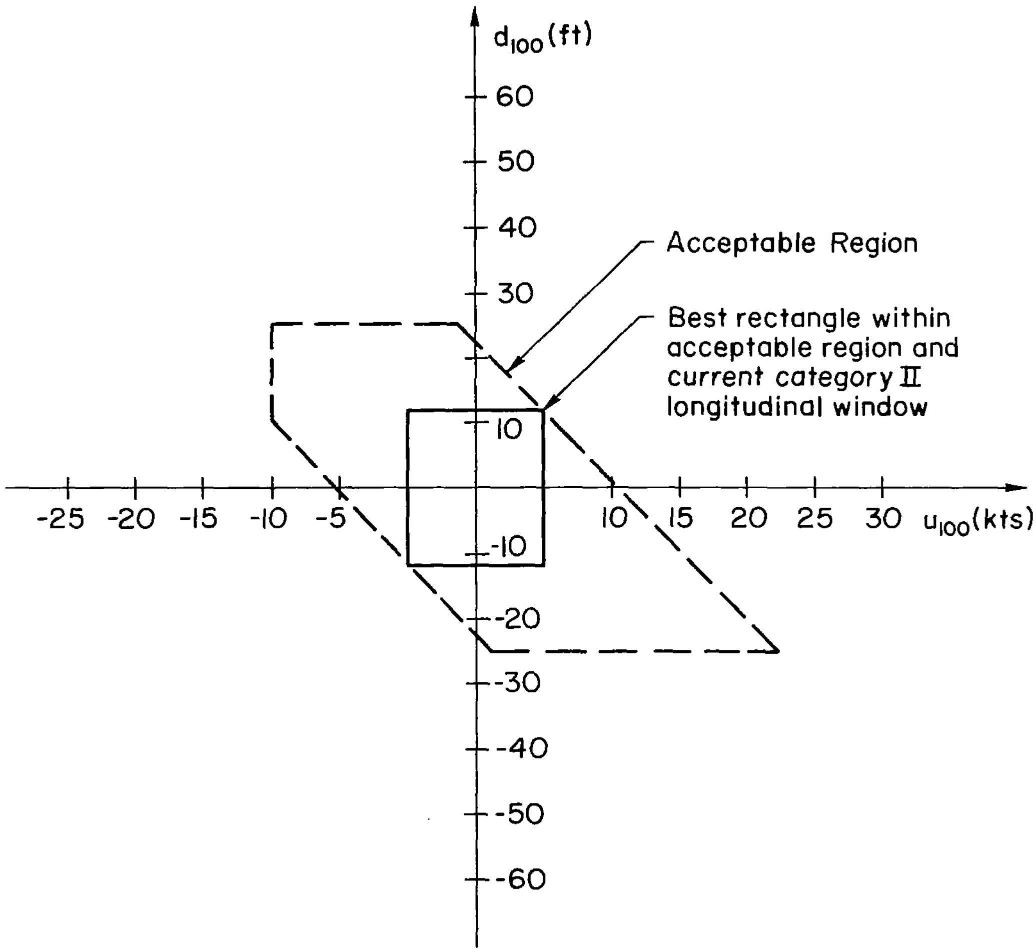

Figure 27. Longitudinal Category II Window ("Best" Rectangle) for Human Pilot Monitor

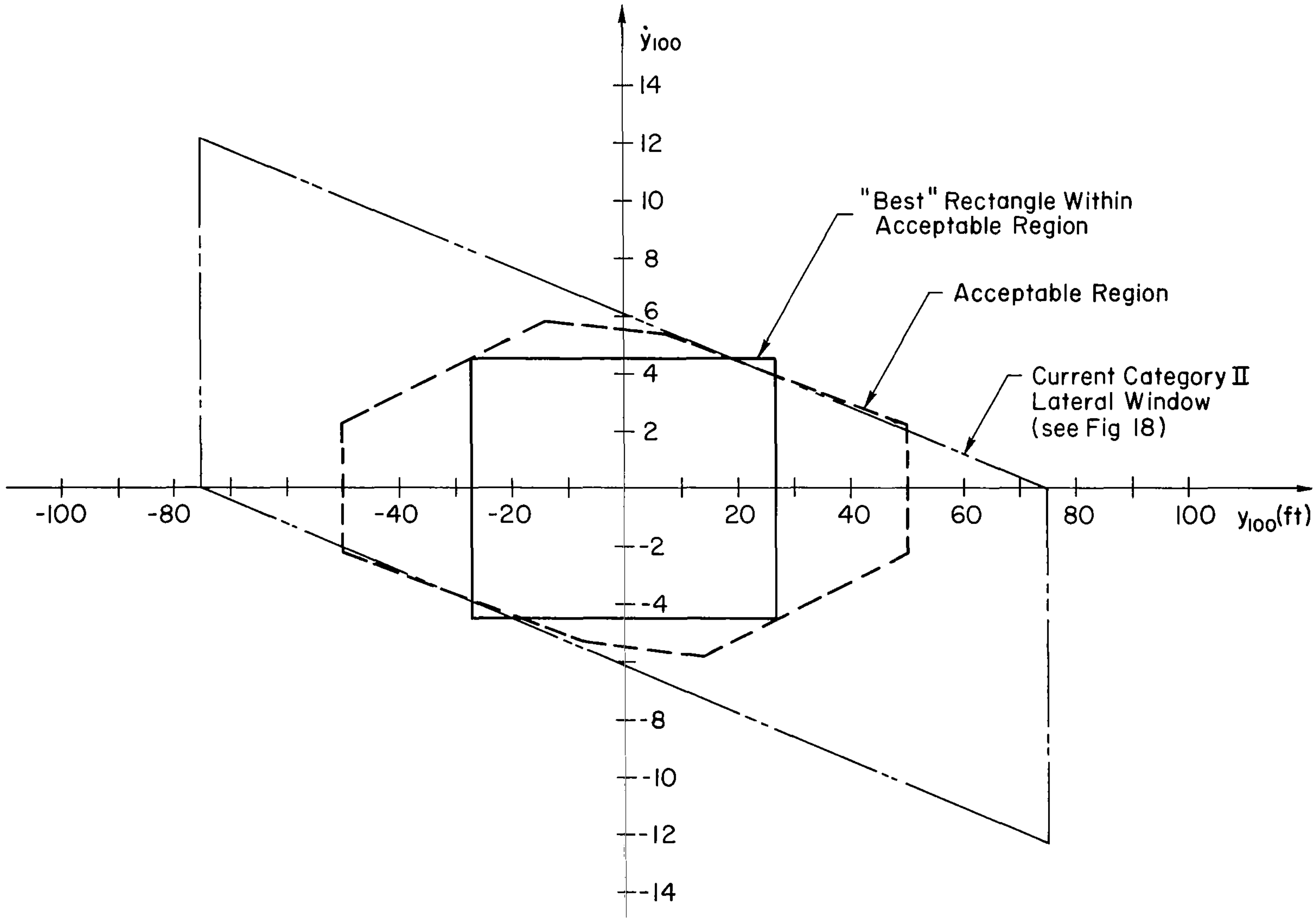

Figure 28. Lateral Category II Window ("Best" Rectangle) for Human Pilot Monitor

approaches due to using the longitudinal rectangular window rather than the entire acceptable longitudinal region. Fifth, the lateral rectangular window is barely larger than a 1σ lateral dispersion. Thus a significant number of missed approaches would be expected (due to lateral dispersions). Sixth, the acceptable lateral rectangular window is very difficult for the pilot to judge by reference to his instruments. That is, the maximum acceptable lateral deviation of ±27 ft corresponds to about 1/7 of a dot on a standard (2 dot full-scale) localizer, and to about 1/4 of a dot on an expanded localizer scale (1/7 of a dot is of the order of one needle width deflection). The maximum acceptable lateral deviation rate of 4.5 ft/sec is probably impossible to judge with current instruments. The best the human pilot can do is to consider the acceptable decision height window to require zero lateral drift rate, and then allow himself a 4.5 ft/sec indifference threshold. Seventh, using the entire acceptable lateral region would significantly reduce the number of missed approaches. Eighth, the current Category II lateral window is considerably larger than the acceptable lateral region. Thus, being within the current lateral window does not ensure a safe touchdown for the example airplane plus controller.

In addition to the above considerations deriving from acceptable touchdown limits, the acceptable guidance equipment tolerances are also of interest. In particular, the lateral guidance tolerances appear to be a key source of flight (and touchdown) dispersions. According to Ref. 2, the allowable localizer beam alignment error, beam bends (about the nominal alighment), and receiver centering error can produce a considerable lateral touchdown error (even without any flight errors due to gusts). The 2σ error limits for each of these items in the touchdown region correspond to 10 ft, 11 ft, and 11 ft, respectively. This would give an RSS (root of the sum of the squares) value of 18.5 ft and a worst case error of 32 ft lateral offset at touchdown. Because the FAA's corresponding 2σ lateral touchdown limit is only 27 ft, these equipment errors leave only about 20 ft for allowable lateral flight errors on a 2σ basis ($27 \doteq \sqrt{10^2 + 11^2 + 11^2 + 20^2}$). The whole point of these comments is to note that equipment tolerances may be significant in determining practical window limits. However, in the present window analyses, equipment tolerances have not been included.

SECTION V

SUMMARY AND CONCLUSIONS

In Sections III and IV two kinds of decision height windows were developed, one for an electronic monitor and one for a human monitor. The window for the electronic monitor comprised the entire acceptable decision height region, while the window for the human monitor was made rectangular (in the longitudinal and lateral state spaces) to enable the pilot to determine whether he is within the window <u>without</u> having to make tradeoff calculations among the window variables. For the example system, using the rectangular longitudinal window does not appreciably increase the probability of a missed approach. However, for the lateral situation the results were not so rosy. Using the lateral rectangular window will lead to a significant increase in the number of missed approaches (compared to using the entire acceptable region).

It is noted that there are several rather serious drawbacks to the current practice of human monitoring of decision height conditions.

- It is difficult to accurately judge fractions of dots on the glide slope and localizer displays.
- The pilot must simultaneously evaluate at least d_{100}, u_{100}, y_{100}, and $\dot{y}_{100}$ (and compare each with predetermined maximum and minimum values), while also looking for the approach lights or monitoring other instruments in the cockpit.
- Due to using a rectangular decision height window there will be unnecessary missed approaches when the airplane is outside the rectangular window, but still within the acceptable region.

The first two drawbacks could be alleviated by using an electronic decision height computer to monitor the rectangle boundaries. However, if a computer is available, then it would be foolish not to use the entire acceptable decision height region, thereby minimizing the missed approach rate. With such a device the human pilot would still make the ultimate decision to continue an approach (or go around), but his job would be made easier because the electronic computer is faster, as well as more accurate in judging the equivalent of needle widths on a display.

Based on the above-mentioned drawbacks and an apparent solution for these drawbacks, it is concluded that a decision height computer should be used for Category II approaches. Of course, if a computer is used, then $\tilde{h}_{100}$ and any other variables of secondary importance would be included (rather than ignored or their effect only approximated). In fact, with a computer, the best strategy to adopt would not be merely to mechanize the inequalities in this report, but would be to mechanize the entire airplane-plus-control-system such that fast-time predictions of touchdown conditions can be made. This would be done using a continuously updated "current" state of the airplane as initial conditions for each succeeding calculation.

Finally, it must be mentioned that the current Category II decision height window is not well suited for the example airplane-plus-control-system. The longitudinal window is well selected, but the lateral window is larger than the computed maximum acceptable decision height region. Thus it is possible to have a "predictable" touchdown incident or accident (based on decision height conditions), and still be within the current Category II lateral window limits.

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APPENDIX A

DEFINITION OF A SUCCESSFUL TOUCHDOWN

A successful touchdown is defined as one in which all pertinent variables are within their respective ranges of acceptable values. If one or more variables exceeds its range of acceptable values it does not necessarily result in an accident because there is a "cushion" built into each of these ranges. A touchdown outside the acceptable range but within the cushion region would be called "marginal," rather than successful. A list of the pertinent variables at touchdown and their corresponding ranges of acceptable values is given in Table A-1.

Because the limits for the acceptable range for each variable do not represent the borderlines for an accident, the limits given in Table A-1 are obviously somewhat arbitrary. They were obtained as a consensus of FAA and industry judgment (e.g., Refs. 2, 3, 4, 5, and 6), with FAA limits taking precedence when they were available. For easy reference, some pertinent excerpts from Ref. 2 are presented here.

"b. Aircraft Touchdown Limits.

(1) Lateral Dispersion.

The aircraft centerline (at main landing gear) should be within 27 feet of the center line of the runway on a two-sigma basis.

(2) Longitudinal Dispersion.

The dispersion of the main gear touchdown point should not exceed 1500 feet total about a nominal point on a two-sigma basis. This nominal touchdown point and the performance limits should be established on the basis of the desired airplane/system characteristics, such that the airplane will touchdown 300 feet or more beyond the threshold and the pilot will be in a position to see at least four bars (on 100' centers) of the 3,000 foot touchdown zone lights at touchdown.

(3) The dispersion limits of (1) and (2) above should consider environmental conditions as follows:

(a) Headwinds up to 25 knots; tailwinds up to 10 knots; crosswinds up to 15 knots; moderate turbulence, wind shear of 8 knots/100 feet from 200 feet to touchdown.

(4) Confirmation of compliance to the above limits may be demonstrated by a combination of:

(a) Computer analysis considering reasonable combinations of wind conditions noted above.

(5) The computer analysis should show that under the most adverse practical combination of the environmental conditions described in 4.b.(3), the aircraft will land with the outboard landing gear no closer than five feet from the lateral limits of a 150 ft. runway."

TABLE A-1

RANGES OF ACCEPTABLE VALUES OF AIRPLANE VARIABLES AT TOUCHDOWN

VARIABLE	MINIMUM ACCEPTABLE VALUE	MAXIMUM ACCEPTABLE VALUE	REASON FOR LIMITING VALUES	COMMENTS
x_{TD} Longitudinal position from runway threshold	800 ft	2300 ft	To insure a touchdown on the runway and within the lighted touchdown zone	The FAA requires a 2σ total dispersion of less than 1500 ft about some nominal point
$-\dot{h}_{TD}$ Sink rate	0	5 ft/sec	Too "hard" a touchdown will damage the landing gear	5 ft/sec is considered to be a limiting value for passenger comfort
θ_{TD} Pitch attitude	0	5 deg	To keep from landing on the nose wheel or hitting the tail on the runway	Pitch attitude at touchdown was always well within the acceptable range of values
u_{TD} Airspeed	125 kt	145 kt	A lower limit is required to avoid stalling or losing control of the airplane. An upper limit is required to avoid overrunning the runway after touchdown	125 kt and 145 kt correspond to u_{nom} ±10 kt, which gives $1.1u_{stall}$ and $1.3u_{stall}$
C_L Lift coefficient	—	$0.83\ C_{L_{max}}$	An upper limit is required to avoid losing maneuver capability	$0.83\ C_{L_{max}}$ corresponds to $1.1u_{stall}$ in 1g flight; and to $1.15u_{stall}$ during 1.1g flight
y_{TD} Lateral position on runway	−27 ft	27 ft	To insure a touchdown and rollout without running off the side of the runway	The FAA requires a 2σ dispersion of 27 ft from the runway centerline
$\dot{y}_{TD}$ Lateral drift velocity	−8 ft/sec	8 ft/sec	To avoid running off the side of the runway after touchdown	8 ft/sec corresponds to about a 2 deg track error
β_{TD} Misalignment angle between inertial velocity and fuselage centerline	−4 deg	4 deg	To avoid excess side loads on the landing gear	Passenger comfort is also a factor
φ_{TD} Bank angle	−5 deg	5 deg	To avoid having a wing tip or engine pod hit the runway	Bank angle at touchdown was always within the acceptable range of values

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